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COMBUSTION OF FEEDLOT MANURE IN FLUIDIZED BEDS

by

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ABSTRACT

Livestock and poultry in confined feeding operations produce 52 million dry tons of economically recoverable manure each year. These animal wastes must be properly managed to prevent water and air pollution problems. Since the cost of transportation precludes the sale of manure as fertilizer, an alternative way of disposing the manure is to use the manure as a fuel for supplying the energy needs of feedlots. While most of the previous research dealt with pyrolysis and gasification with partial oxidation, the present research deals with direct combustion of manure. Under the present research program, thermophysical and pyrolysis data were generated for the feedlot manure. Experiments were carried out for the direct combustion of manure in a fluidized-bed combustor (FBC). Data were obtained for the composition of products. Knowing the fuel composition, the fuel feed rate, the bed and carrier air flows, and the exhaust gas composition, the carbon oxidation and gasification efficiencies were calculated using $N_2$ conservation principle. The effects of excess air and bed temperature on the performance of FBC were investigated.

INTRODUCTION

Livestock and poultry in confined feeding operations produce 52 million dry tons of economically recoverable manure each year (Van Dyne, et al., 1978). These animal wastes must be properly managed to prevent water and air pollution problems (Fu, et al., 1974). Most of the manure is utilized on agricultural lands as fertilizer. Other uses of manure include feedstuffs and feedstock for both biological and thermochemical processes.

Manure solids can be pyrolyzed, and gaseous liquid products may be used as an energy source. The pyrolyzed manure solid can be used as a carbon black substitute and as a filler material. In paint, ink, and rubber applications, it serves in both capacities. An efficient way is to combust manure directly and extract the energy near the feedlots.

Direct combustion of manure from open dirt-surfaced feedlots could produce a steam output of 6.5 million KJ/ton (as-received basis) or an electrical output of 1.7 million KJ/ton. On the other hand, anaerobic digestion of feedlot manure yields only about 0.633 million KJ/ton as electricity. Hence,

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direct combustion of manure seems to be an attractive approach for energy conversion.

The annual fuel cost for Texas cattle feedlots is about $6 to $8 per head of cattle on feed. Most of this fuel is consumed to process for feedstuffs at the feedlots (Sweeten, et al., 1980). Direct combustion of all manure collected at cattle feedlots in Texas could produce six times more energy in the form of steam and electricity than is required for feed processing; thus, the excess energy can be fed into the general electrical network. However, feedlot manure is a low-grade fuel due to the high moisture and ash content (Sweeten, et al., 1980). Also, the emissions of sulfur, nitrogen oxides, and particulates may exceed air quality standards set up by the EPA. Hence, the combustor must be capable of handling low-grade, high-ash solid fuels (without slagging) and at the same time reducing the emissions of pollutants. Thus, the fluidized-bed combustion appears to be a suitable technology for direct combustion of manure. The present research deals with combustion experiments in a fluidized-bed combustor at the Turbomachinery Laboratory (Research Annex) of Texas A&M University. Results have been obtained for the effects of various operating parameters on the combustor performance.

LITERATURE REVIEW

Most of the previous research has dealt with pyrolysis and gasification or partial oxidation (Walawander, et al., 1973; Huffman, et al., 1978; Kreis, et al., 1979; Raman, et al., 1982). Walawander, et al. (1973) presented an economic evaluation of ammonia synthesis gas recovery process. Their evaluation was based on a design capacity of 1,100 tons of wet manure per day.

Miles (1980) conducted combustion experiments to determine the appropriate conditions for burning stockpiled feedlot manure and to assess combustion efficiency, emissions performance, and bottom ash problems. Experiments were conducted by large pile burning and in a concentric vortex combustion unit. The manure did not burn readily as combustion was limited by low fuel porosity and the presence of moisture and ash. A porous or agitated fuel bed was recommended. Three types of combustion units were suggested for further evaluation: fluidized bed, rotary kiln, and multiple hearth furnace.

A limited number of feedlot manure combustion experiments were conducted in a circulating mode in a pilot plant fluidized-bed combustion unit at an industrial facility (Sweeten, et al., 1984). A total of four experimental runs were conducted. Since experiments were conducted on a relatively large-scale industrial facility, the experimental conditions were not easily controllable. The experimental data did indeed show the feasibility of combustion of manure in a fluidized-bed unit. There is no experimental data available on combustion of manure in a fluidized-bed combustion (FBC) unit under controlled and measurable operating conditions. Further, no parametric studies have been carried out for the combustion and gasification efficiencies of manure in a FBC unit so that peak operating conditions can be determined.

OBJECTIVES

The ultimate goal of the research program is to develop a database on manure fuel characteristics and to provide a technology for the combustion of feedlot manure for an on-site FBC facility. Fuel characteristics and theoretical combustion performance had been previously studied by Raman, et al. (1980, 1981) and by Park (1984).

The objectives of the present research are to obtain thermophysical data on manure, conduct combustion experiments, and obtain the performance results for various parametric cases.
The following tasks were carried out in order to achieve the research objectives:

- Ultimate and proximate analyses were conducted on feed lot manure (Table 1). Further TGA and DSC analyses were carried out to determine the devolatilization.

**Table 1. Chemical Analysis of Manure.**

<table>
<thead>
<tr>
<th></th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate (Wet Basis)</td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>18.02</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>34.10</td>
</tr>
<tr>
<td>Ultimate (Wet Basis)</td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>27.01</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.02</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.60</td>
</tr>
<tr>
<td>Oxygen</td>
<td>14.32</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.64</td>
</tr>
<tr>
<td>Chlorine</td>
<td>1.32</td>
</tr>
<tr>
<td>Chemical Formula</td>
<td>CH₁.₈₁₀.₃₂₉₈</td>
</tr>
<tr>
<td>Stoichiometric Air</td>
<td>8.14</td>
</tr>
<tr>
<td>Fuel Ratio (Dry Ash Free Fuel)</td>
<td></td>
</tr>
<tr>
<td>Heating Value (KJ/kg,</td>
<td>12,395</td>
</tr>
</tbody>
</table>

characteristics (Figure 1) (Park, 1984).

- The coal-fired fluidized-bed combustor (FBC) unit at the turbomachinery laboratory was modified so that feedlot manure could be fired as a fuel.

- Cold- and hot-flow experiments were carried out to determine the fluidization characteristics, and the results were checked against the available theoretical calculations.

**Figure 1. Thermogravimetric Analysis of Manure.**

- Experiments were then carried out in order to obtain data on combustion characteristics of manure.

- Parametric studies were carried out with excess air, fluidization velocity, and bed temperature as the three operating parameters.

- Combustion performance was evaluated by measuring the bed temperature and the combustion of the exhaust gases. The estimation of the oxidation and gasification efficiencies are based on the analysis of exhaust gases.

**EXPERIMENTAL SETUP**

The FBC had been previously used for firing lignite as a fuel (Richardson and Jenkins, 1982). The unit has been modified for firing manure as a fuel. Figure 2 gives the schematic diagram of the current FBC system.

**The Reactor**

The present feeding system for fuel consists of a 55-gallon drum which serves as a hopper. This drum is pressurized so that a positive pressure of about 1 inch of water is maintained.
Preheating of the bed is achieved by two methods: electrical heaters and gas burners.

The reactor walls are surrounded by four quarter-circular Lindberg heaters cemented externally to the bed wall chamber. Each heater is rated at 2,100 watts on 230 volts single-phase line. Four variable autotransformers, operating on a 220-volt supply, regulate the power supply to the electrical heaters.

A domestic gas dryer burner with a rating of 25,000 Btu/h is being used. The burner is housed inside the capacitance tank (Figure 2). A high-pressure natural gas line (13 psi) with a pressure regulator is used so as to avoid the decrease in gas flow rate.

The gas heater is used to accelerate the preheating. Further, it can be used to maintain the bed temperature when the quality of manure fired is of poor grade.

Diagnostic System

Temperatures are measured with sheathed CrAl thermocouples. The volumetric air flow rate is measured with rotameters installed in the air flow lines. The auger feeder has been calibrated with fuel in the feed hopper. Also, a check is kept on the fuel feed rate all the time during experiments by weighing each batch of fuel and checking the time taken for the feeding.

Exhaust gas samples are taken out at the inlet and outlet of the water quench system by syringes for analysis by a Hewlett-Packard gas chromatograph. Chromatographic data give the dry volume percentages of each component of gas in the exhaust. This is then used to calculate the degree of carbon gasification and oxidations.

EXPERIMENTS

The experiments were divided into two parts: the cold-flow (fluidization) experiments and the hot-flow (combustion) experiments.
Fluidization

Sand was used as the bed material. ASTM standard sieve analysis (E-11 test) was performed to determine the particle-size distribution of the sand. The analysis showed that the diameter of most of the particles of bed material has a value of approximately 500 μm.

The minimum fluidization velocity was experimentally determined to be 35 cm/s (6.38 l/s, 810 FPH).

Under the combustion conditions, the high bed temperature decreases the air density and, thus, the same mass flow of air has a higher velocity. Further, the viscosity of air increases as the bed temperature increases. This leads to the fluidization of the bed at lower air flows. It was found that during the experimental conditions, fluidization was achieved at a velocity of 25 cm/s (air flow rates of 4.4 l/s [560 FPH]).

Combustion

Experiments were undertaken to determine the effects of the following parameters on the combustion of feedlot manure:

- Percent excess air.
- Bed temperature.

Excess air was altered by keeping air flow constant and varying fuel feed rates. Three sets of experiments were performed to study the effects of each of the parameters. The base conditions taken were: 32 percent excess air, 650°C bed temperature, and air velocity of 1.46 times the minimum fluidization velocity.

The experimental procedure is as follows: The bed material (sand) is first loaded into the bed such that the sand bed height is kept at 0.46 m. The preheating is started by using the electric heaters at 90 percent. When the required sand bed temperature is achieved, manure feeding is started at a controlled rate, and electrical heaters are readjusted. The desired water flow rate is then set for the water quench system (to cool the exhaust gases and to collect the sand and fuel).

RESULTS AND DISCUSSION

During the preheating, the bed temperature initially increases rapidly, and then the rate of increase tapers off.

During combustion of feedlot manure, the temperatures at the reactor walls and inside the reactor were constantly monitored.

Initially, freeboard temperature ($T_{FB}$) was considerably lower compared to the bed temperature ($T_b$). As soon as manure was fired, the bed temperature increased, and the freeboard temperature approached rapidly to the bed value and is usually almost the same as the bed temperature during combustion. This indicates that most of the combustion takes place inside the bed and, as such, the heat can be extracted from the fluidized bed (where we have a very high heat transfer coefficient).

A total of about 18 experiments were performed.

During experiments the fuel feed rate was checked periodically by weighing the fuel loaded in the hopper and noting down the time it takes for the fuel feeding.

General Combustion Characteristics

Based on the results obtained and experience gained with manure as a fuel, the following general observations could be made regarding combustion of manure.

Manure is an easily combustible fuel. It is the high-moisture and high-ash content of the fuel which causes the problems. The fouling problems can be minimized by combusting the fuel at the lowest possible bed temperatures. The volatile matter constitutes up to about 80 percent of mass of the dry ash free
fuel. Sufficient residence time must be provided for the volatile species to combust completely. Hence, air velocity must be kept at as low a value as possible. But, in order that the bed is completely fluidized and well mixed, the air velocity should be kept higher than the minimum fluidization velocity. Lower fluidization velocity is achieved by using finer bed material.

The minimum bed temperature required to ignite the manure was found to be about 570° to 600°C. Since the unit was made of stainless steel and the diameter of the bed was only 0.15 m, the heat loss rate at higher bed temperature (> 615°C) was too high for the fuel feed rates considered (maximum obtained fuel feed rate was 2.2 g/s). Thus, electrical heaters were set at various power levels in order to achieve the bed temperatures up to 700°C.

The exhaust gas analysis revealed the presence of significant amounts of CO₂, CO; and somewhat smaller amounts of H₂, CH₄, and C₂H₄. The exhaust gas analysis was used to calculate the carbon gasification and carbon oxidation efficiencies which are defined as follows:

- Gasification efficiency = (Carbon in all gaseous species/carbon in the fuel feed).
- Oxidation efficiency = (Carbon in CO₂ and CO/carbon in the fuel feed).

(The combustion efficiency is normally defined as the ratio of actual heat release rate to the theoretical heat release rate.) The estimation of gasification and oxidation efficiencies from the exhaust gas analysis requires a knowledge of air fuel ratio and combustible content of the fuel. A summary is provided below:

From the proximate analysis and the actual wet fuel flow rate, the dry fuel flow rate can be determined. The carbon feed rate can then be determined from the knowledge of the ultimate analysis. From the exhaust gas analysis, the carbon efflux rate in the gaseous stream can be estimated. The ratio of carbon flow rate in exhaust gases to the carbon feed rate then provides a value for gasification efficiency. For convenient reference, this method will be called UPEA method (ultimate-proximate exhaust gas analysis). The excess air was determined from the measured air flow and fuel flow rates.

The values so computed yielded values higher than 100 percent. Hence, only the ratio of efficiency at any given condition to the efficiency at the base conditions will be reported here.

Effects of Excess Air

Proximate analyses carried out for the manure used in the experiments reveal that the effect of aging of manure on the combustible content is not very significant. Two methods are possible for determining the excess air. Using ultimate and proximate analyses, the stoichiometric air can be calculated. By measuring air flow, excess air can then be determined (UPEA method). Alternatively, if it is assumed that the carbon input is completely gasified, then the percent excess air can be theoretically predicted using only the exhaust gas analysis data without assuming the chemical composition of the manure. For convenience, this will be referred to as EA method. Unless otherwise reported, UPEA method is used for calculating the percent of excess air. Figure 3a shows the effects of excess air on the composition exhaust gases.

When the excess air is about -20 percent, significant amounts of H₂, CH₄, C₂H₄, etc., are produced. As the percentage of excess air is increased, the percentage of H₂ and hydrocarbons falls off. The CO₂ in the gas decreases somewhat rapidly as excess air is increased to about 10 percent (O₂ content, 6 percent), but the CO concentration appears to be rather insensitive for further increase in air. As excess air is increased beyond 8 percent, more
volatiles and char particles oxidize in the emulsion phase to CO. However, it was shown in earlier works that the oxidation rate of CO is proportional to O₂ concentration in the gas up to about 5 percent, but the rate of CO oxidation remains insensitive to O₂ concentration beyond 5 percent (Sobolev, 1959). Thus, CO concentration is expected to increase. But, dilution due to excess air has the opposite effect, and, thus, CO in the gas appears to remain insensitive to the increase in excess air. The CO percent falls off with the increase in excess air mostly due to the dilution effect.

The excess air is increased by keeping a constant air flow rate while decreasing the fuel feed rate. Hence, as excess air increases, the dilution effect can bring down the concentration of H₂, CH₄, CO, etc. Hence, a plot of ratio of CO/CO₂, H₂/CO₂, etc., will reveal the effects of excess air without the dilution effects. Figure 3b plots the results.

Again, the concentration of H₂, CH₄, C₂H₄ falls off with the increase of percent excess air, and the CO concentration has a minima. The minima behavior can again be explained as being due to the dependence of CO oxidation on O₂ percent.

Figure 4 shows the carbon dioxide percent volume with respect to excess air as determined by the UPEA method and as determined by EA method.

The curves are nearly identical. The EA method shifts the curve to the lower excess air percent.

Figure 5 plots the results of the carbon gasification and oxidation efficiency ratios with excess air percent. A possible explanation for the maximum in the oxidation efficiency is as follows: Since manure contains 80 percent volatiles, the efficiency is dominated by the kinetics of oxidation of volatiles. The oxidation rates are proportional to concentration of volatiles and oxygen. At low excess air, sufficient O₂ is not available for oxidation. As excess air is increased, the increased availability of O₂ dominates the oxidation process and, hence, oxidation efficiency increases. At
Figure 4. Effects of Excess Air on Mean Volume Percent.

Figure 5. Effect of Excess Air on Efficiencies.

High excess air, the volatiles concentration falls off again, decreasing the oxidation rate of volatiles, and, hence, the oxidation efficiency falls again.

Figure 6 plots the ratio of oxidation to gasification efficiency.

Both UPEA and EA methods will yield the same curve shown in Figure 6.

Figure 6. Effect of Excess Air on Efficiency Ratio.

Effects of Temperature

Figure 7 shows the results for the effects of bed temperature.

As temperature is increased from 615°C (0 percent heater setting) to 700°C (70 percent heater setting), the O₂ in the gas first decreases indicating more combustion, then increases again. The H₂ and hydrocarbon contents in the gas, though small, seem to increase slightly. The slight increase may be due to pyrolysis of fine material deposited on the exhaust pipes exiting from the bed. (It should be noted that pyrolysis for manure starts around 200°C [see Figure 1]). It should further be noted that the sum of CO₂ and CO increases as the bed temperature increases. Beyond 650°C, there seems to be no apparent gain in the sum of CO₂ and CO. Bailey (1968) reports that the CO for coal-fired FBC can be as high as 1 percent when bed temperature...
Figure 7. Effect of Bed Temperature on Gas Composition.

is about 700°C, and the CO content decreases to 0.1 percent as bed temperature is increased to 800°C. Coal constitutes only up to 30 to 40 percent volatile matter, while manure consists of up to 80 percent. Since volatiles rapidly oxidize to CO, and CO oxidation rate is slow, higher CO content is expected for manure-fired FBC.

Figure 8 shows the effect of bed temperature on efficiencies.

As expected, the increased bed temperature results in better carbon conversion efficiency. It is noted that ratio of oxidation to gasification efficiency appears to fall off as the bed temperature is increased beyond about 655°C:

SUMMARY

The following is a summary of the results obtained for the combustion of feedlot manure in a fluidized-bed combustor (FBC):

- The product of pressure drop x area was found to be close to the bed weight value. Thus, nearly perfect fluidization was achieved.

- Manure could be ignited at about 580°C. The high-moisture content of the manure created complications, especially in the feeder system. Hence, fuel was always dried before being used for experiments (the moisture content, after drying, was usually about 11 percent).

- Combustion was self-sustaining (with heaters at zero setting) at fuel feed rates above 2 g/s. However, for rates below 2 g/s, electrical heaters are necessary to maintain the desired bed temperature.

- About 13.5 percent excess air, 650°C bed temperature, and 1.46 μm were fixed as the base conditions. Each parameter was then varied by keeping the value of the other two parameters at base conditions.
• Oxidation efficiency increases when excess air is varied from -20 percent to 10 percent. Above 10 percent excess air, the efficiency falls off. The CO concentration is insensitive to the increase of excess air after about 10 percent excess air.

• The CO₂ production and the oxidation efficiency increased when the bed temperature was varied from 615° to 650°C; above 650°C, CO₂ flattens.

• If the level of CO is acceptable (3 to 4 percent), then about 10 percent excess air (the excess percent air value is based on the assumptions that the stoichiometric air to dry ash free fuel ratio is 8.1) and 650°C gives optimum conditions for combustion of manure in the FBC unit.

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