Historical Background

The first full scale multiple hearth (Herreshoff) furnace (MHF) used for sewage sludge incineration was placed into operation in Dearborn, Michigan in February 1935. The first fluid bed sludge incinerator (FBSI) was manufactured by Dorr-Oliver and installed at Lynnwood, WA in 1962. Before the enforcement of stringent air pollution regulations the MHF enjoyed wide popularity because the counter-current flow in the furnace resulted in low furnace exhaust temperatures, which in turn reduced the need for auxiliary fuel. Additionally, per square foot of floor space a MHF could (and still can) process more sludge than can a FBSI. Although FBSI could operate at a lower excess air (flue gas oxygen), the net result of the need to operate with exhaust temperatures in excess of 1,400ºF was greater auxiliary fuel costs. The added cost of pressurizing the fluidizing air was another factor that slowed the initial adoption by wastewater treatment plants (WWTP) of the FBSI.

When environmental regulations necessitated afterburners and higher exhaust temperatures for the MHF, and the auxiliary fuel playing field became more leveled, FBSI became the furnace-of-choice for almost all new WWTP installations. However, a substantial body of the total sewage sludge incinerated in the U.S. is still done in MHF. Therefore the need to minimize auxiliary fuel use in both MHF and FBSI remains an important issue from both an Operations and Engineering perspective.

Introduction

During the contractual, design and operational phases both multiple hearth and fluid bed incinerators have been treated during as isothermal black boxes. The heat and material balances commonly used consider only bulk, average furnace temperatures before the flue gas enters an afterburner, heat recovery, or emission control device. In actuality, a MHF has an extremely wide temperature variation between the top, middle and bottom hearths. In a FBSI the freeboard temperature is invariably higher than the bed.

The following are examples of operating practices sometimes used to make sludge incinerators easier to operate and control:

♦ Deliberately detuning the dewatering process so as to increase the moisture content of the sludge being fed to a MHF

♦ Spraying water into the freeboard of a FBF to reduce offgas temperature while simultaneously adding fuel oil to the sand bed

♦ Using higher-than necessary excess air (flue gas oxygen)
When the goal is reducing in auxiliary fuel use, these practices are obviously counter-productive. The purpose of this paper is to provide the sludge incineration community with a more in-depth understanding of the different thermodynamic zones within MHF and FBSI so that wasteful fuel practices such as those described above can be avoided. With this understanding of the physical and thermodynamic processes within these furnaces comes the knowledge of to make the kinds of changes to the air and fuel flow distribution that make the simultaneous reduction of both fuel and incomplete combustion related pollutants possible.

To develop this understanding and use it to define and predict cause and effect relationships it is necessary to expand the traditional isothermal black box heat and material balance. As a minimum the expanded analysis must recognize that there are separate process steps.

- Evaporation of moisture
- Combustion of volatiles
- Combustion of fixed carbon

Additionally, the expanded analysis must include not only First Law thermodynamics, but also heat and mass transfer related calculations.

**Tyranny of the Thermocouples**

The successful operation of any furnace depends on obtaining accurate, reliable, and most importantly truly representative information about combustion temperatures. A good instrument department can address accuracy and reliability issues. However, obtaining truly representative temperature information about a MHF is just about impossible. Figure 1 illustrates a typical thermocouple placement for a MHF. Assuming that the hearth has a circumferentially uniform temperature (sludge uniformly distributed throughout the full 360°) the thermocouples on an IN hearth (where the gases flow OUT) give a representative reading. However, the thermocouples an OUT hearth, (where the gases flow IN towards the shaft) read a combination of the temperature of the flue gases coming up through the drop holes from the hearth below and flame radiation from burners mounted along side. They **do not** read a temperature that is reasonably representative of the flue gases leaving the hearth. Further compounding this problem is the fact that the majority of MHF use these erroneously reading OUT hearth thermocouples to control auxiliary fuel burners located on the same hearth.

Unfortunately there is no easy solution to the problem of obtaining a representative OUT hearth temperature. One facility tested a very long thermocouple, supported with small stainless steel eyebolts drilled through the roof. The benefits gained were difficult to quantify while the maintenance problems were obvious and no further work was done. The best and simplest solution is to simply control OUT hearth burners by the thermocouples on the IN hearth above.

Similarly, a thermocouple mounted in the freeboard of a FBSI is affected by bed radiation and may not read a true gas temperature. Locating the thermocouple in the horizontal downstream breaching, just far enough to be out of line-of-sight of the bed will yield more accurate gas temperatures. Thermocouples located in the ducting immediately upstream of a venturi scrubber will read low if they can “see” the cold throat and water sprays.
Journey to the Inside of a MHF

To understand how a MHF works, it is necessary to understand what makes the fire move. Perhaps the easiest way to begin is to imagine that the spiral path of the sludge has been straightened resulting in a very long belt conveyor furnace (~1,000 Ft.) as schematically illustrated in Figure 2. For ease of understanding and explanation, the furnace is assumed to have an external afterburner and no burners are fired in the furnace section. With the counter-current sludge and gas flow, the outgoing hot flue gases dry the incoming wet sludge. At some point the percent total solids (%TS) in the sludge will become high enough that the sludge will start to burn. This point is defined as the Onset of Combustion (OC). The calculation for the %TS at the OC is complex. It is based partly on personal experience combined with an examination of the conditions necessary for a stable flame immediately above the surface of the sludge. For the sludge used in the calculations in this paper:

- 78% Combustible
- 10,519 BTU/Lbm. Combustibles

a value of approximately 45% TS for the OC has been used. If the percent combustibles were only 65%, a value of 50% TS for the OC would be more appropriate. For many of the examples contained herein, the %TS of the incoming sludge has been deliberately selected low to emphasize the drying process.

The highest temperature in the belt furnace is at the point of the OC. Referring to the belt furnace, the gases exiting to the left of the OC are cooled as they evaporate moisture from the incoming sludge. Gases approaching the OC point from the right have not burned all of the combustibles and therefore have not reached maximum temperature. The temperature at the OC point is the Theoretical Temperature of the Products of Combustion (TTPC); also know as the adiabatic flame temperature, for a 45% TS cake at the excess air conditions at that location. If we had roof-mounted thermocouples every foot, the exact location in this hypothetical 1,000' long furnace could be determined by measurement. It is important to remember that the high OC temperature shown in this hypothetical furnace assume gas phase combustion in the vapor space above the burning bed is instantaneous and that the thermocouple reads only the true gas temperature at that location.

As described previously, in a real world MHF, representative temperature readings are not necessarily available and specifically not available at the outlet of an OUT hearth where the gases pass upward through the annular space around the central shaft. Unless the point of OC happens to fall at a thermocouple location, the temperatures read will always be lower. However, this “tyranny of the thermocouples” does explain how slagging can occur even when the wall-mounted thermocouples do not show excessive temperatures.

Another important point relating to the concept of Onset of Combustion is that it depends only on the sludge properties at that point. For a sludge with specific thermodynamic properties, the %TS at the OC will be the same regardless of initial moisture content. A change in %TS will change the location of the OC but will not change the TTPC.
Hearth-by-Hearth Heat and Material Balances

The hearth by heart heat and material balances used to develop the following graphs, calculate conditions for the solids and gases as they enter and leave a hearth. The only intermediate parameter calculated within the program is the location of the OC. Therefore, in many of the graphs used in this presentation it was necessary to adjust the parameter being varied so that the OC ended up just as the sludge was entering a hearth. In this manner the temperatures and gas composition at this point could be displayed. During actual operation it is undesirable to have the OC occur just below the drop holes (entering IN hearth) because the flames coming up through the small holes will cause slagging. However, to illustrate concepts in this paper, this “real world” constraint has been ignored. The 11-hearth furnace used for the illustrative examples has a net hearth area of 267 Ft²/Hearth (22'-3” MHF).

Effect of Flue Gas Oxygen

Small changes in flue gas oxygen (wet) have a pronounced effect on the movement of the fire within a MHF as shown in Figure 3. Heat transfer to the sludge by radiation, from the roof, gases and flames accounts for 80% to 90% of the water evaporation. For the sludge described previously, a 1% change in oxygen results in approximately a 121°F change in the OC temperature. The Fourth Power relationship of radiation to temperature amplifies the water evaporation rate such that a 1.3% change in oxygen results in the fire moving one entire hearth.

Effect of Feed Rate

Changes in feed rate also contribute to the movement of the fire as shown in Figure 4. An increase in feed rate means that more pounds of water must be evaporated before the OC is reached and more hearth area is required to accomplish that. As shown on the figure, a 19% change in feed rate causes the fire to move an entire hearth.

Effect of Percent Total Solids (%TS)

Small changes in %TS result in large movement of the fire as shown in Figure 5. A change in total solids as small as 1.5% can cause the fire to move an entire hearth. If the position of the fire is held constant, as in Figure 6, the feed rate increases exponentially with increases in % TS. The very high feed rates shown at high %TS results in a large percentage of the volatile combustion taking place on the IN Hearth #8. This would result in flames coming up through the drop holes on OUT Hearth #7 and that would soon cause severe slagging.

More “Tyranny of the Thermocouples”

Many times operators think they are solving a high temperature problem by simply changing the feed rate or the %TS. In actual fact, most of the time all they are doing is fooling themselves because all that really has been accomplished is to move the OC (hottest point) away from a thermocouple as shown in Figure 7. You can “fool” the thermocouple strip chart but you can’t fool thermodynamics.
Firing of Auxiliary Fuel in a MHF

One of the more misunderstood phenomena of sludge incineration in a MHF is which hearth to fire auxiliary fuel on. In earlier years, with low solids, high excess air, and low furnace exhaust temperatures, the axiom was, “keep the fire and firing of auxiliary fuel low in the furnace”. Now that high exhaust temperatures (external or top-hearth afterburner) are required to meet emission regulations and rolling averages must be maintained within limits, just the opposite is true. With radiation the primary mode of heat transfer; water evaporation rate increases in proportion to the fourth-power of the absolute temperature. Figure 8 illustrates a MHF with a 1,400ºF afterburner temperature. As indicated by the hearth #5 and hearth #3 temperatures, feed rate can be substantially increased when a greater percentage of the auxiliary fuel is fired in hearth #5, the first available burner hearth above the Onset of Combustion. The scenario in this figure that fires all of the auxiliary fuel on hearth #5 is not practical because of the high hearth temperatures that result. However, the next lower curve, which represents 75% on hearth #5 and 25% on hearth #3, is indeed a realistic approach.

Although not shown in this figure, if the feed rate is kept constant, changing the firing rate distribution of the burners will cause the fire to dramatically move. It is important to note that in this figure, the exhaust oxygen (wet) has been decreased to 6% whereas previous figures used 7%. The burners have been fired with 20% excess air, which causes a drop in the level of oxygen passing the OC and exhausting the furnace. In this example, the level of oxygen passing the OC is actually in excess of 7% used in the other examples.

Fuel Economy, Stability and Furnace Operation

As shown by the foregoing, in a MHF small changes in oxygen, feed rate, %TS, and auxiliary fuel distribution cause the fire to move. When flue gas oxygen is reduced to save auxiliary fuel, the stability problem is exacerbated and as a result the furnace operates in a meta-stable mode as illustrated in the “marble in bowl” concepts shown in Figure 9. However, when the cause and effect relationships described herein are understood and therefore can be predicted, operation in fuel saving modes such as higher %TS and/or lower excess air becomes possible.

The Multi-Zone Fluid Bed Sludge Incinerator

The concept of a multi-zone fluid bed incinerator with overfire and freeboard sprays is shown in Figure 10. The first zone is the bubbling sand bed. The second zone is sometimes called the splash zone and represents the freeboard prior to the introduction of overfire air. Overfire air is introduced into the third zone. Water sprays are used in the upper fourth zone. A minimum temperature is required to maintain combustion stability in the bubbling sand bed. A safety margin is usually added to allow for the cooling that will occur when the furnace goes through a purge cycle after an unintentional shutdown.

While conventional FBSI heat and material balances assume that all sludge combustibles and auxiliary fuel are burned in the sand bed, in fact they are not. The typical temperature rise from bed to freeboard due to delayed combustion occurring in the freeboard is approximately 300ºF. When a FBSI is operated in a mode wherein
auxiliary fuel is added to the bed to maintain minimum bed temperature, and water sprays are operated in the freeboard to protect downstream equipment (i.e. heat exchanger), auxiliary fuel is being wasted.

**Cause and Remedies of High Freeboard Temperatures**

The underlying cause of high freeboard temperatures is the fact that all of the fuel is not burned in the bed. Delayed combustion in the freeboard causes the temperature to rise. Typically it is the sludge solids that are the culprit, as this phenomenon is not observed when just firing auxiliary fuel. Figure 11 illustrates the results of delayed combustion of the dry solids on bed temperature at constant exhaust conditions. Figure 12 assumes that 20% of the total solids are burned in the freeboard and shows the relationship of freeboard temperature to bed temperature.

If the minimum allowable bed temperature is 1,300°F, sufficient auxiliary fuel must be added to raise the freeboard (Zones #2 & #3) temperature to 1,549°F. In practice, water sprays (Zone #4) might be added to cool the exhaust temperature down to 1,500°F to protect the downstream heat exchanger. **However, an additional 16.5% of auxiliary fuel has been wasted.**

The obvious first step in mitigation is to improve the distribution of sludge within the bed. It is unrealistic to believe that a simple split in a sludge line from a cake pump will divide sludge to different bed locations. One side will eventually plug and the cake will only end up being delivered through a single nozzle. High-alloy nozzles that penetrate significantly into the bed have been shown to have a beneficial effect.

**The Overfire Air Solution**

After all reasonable and economically viable means to improve sludge combustion within the bed have been exhausted, and the problem still exists, small, high velocity, overfire air nozzles may be added to reduce auxiliary fuel consumption. When combustion is delayed, the oxygen in the bed becomes higher than the exhaust oxygen. Therefore splitting a fraction of the air off as overfire air reduces the excess air in the bed thereby increasing bed temperature. Figure 13 illustrates bed temperature as a function of overfire air rate at constant furnace exhaust conditions. As indicated, an overfire air rate of approximately 24% would bring the bed temperature up to the required 1,300°F. Caution must be used so as not to deplete the bed oxygen to the point where the amount of delayed combustion starts to increase.

**Summary and Conclusions**

Through the use of illustrative graphs, this paper has demonstrated that during actual operation MHF and FBSI are not isothermal black boxes. However, with an understanding of the internal thermodynamics and heat transfer rates, operation can be improved while simultaneously reducing auxiliary fuel consumption and both of these can be accomplished while still keeping operating parameters within limits that will not damage the equipment.
Figure 1: Multiple Hearth Furnace Temperatures

Figure 2: Conceptual Belt Furnace
Figure 3: MHF with Varying Flue Gas Oxygen

Effect of Varying Oxygen at Constant Sludge Feed
Legends = Oxygen (wet)

No auxiliary fuel fired

1.3% change in wet oxygen causes fire to move one (1) hearth
Oxygen adjusted to yield Onset of Combustion at hearth entrance

Figure 4: MHF with Varying Feed Rate

Effect of Varying Feed at Constant Oxygen
Legends = Wet Cake Feed Rate, Lbm./Hr.

No auxiliary fuel fired

19% change in feed rate causes fire to move one (1) hearth
Feed adjusted to yield Onset of Combustion at hearth entrance
Figure 5: MHF with Varying Percent Total Solids

Effect of Sludge %TS at Constant Feed Rate and Oxygen
Legends = Wet Cake %TS

- No auxiliary fuel fired
- 21,825#/Hr. wet cake
- 7% Flue Gas Oxygen (wet)

%TS adjusted to yield Onset of Combustion at hearth entrance
Approximately 1.5% change in Total Solids causes fire to move one hearth

Figure 6: MHF with Varying Percent T.S. and Feed Rate

Effect of %TS on Maximum Feed Rate
Oxygen constant @ 7% (wet)

- No auxiliary fuel fired
- 20%TS; 15,150#/Hr.
- 22.5%TS; 21,825#/Hr.
- 25%TS; 30,055#/Hr.
- 27.5%TS; 40,575#/Hr.

Exponential rise in feed rate with increasing %TS
Feed rate adjusted to yield Onset of Combustion at hearth entrance
Figure 7: Effect of Onset of Combustion on Hearth Temperature Readings

Effect of OC in Middle of Hearth on Temperature Readings
Illustrates the "Tyranny of the Thermocouples"

Gas Leaving Temperature, Deg. F

Hearth Number

Oxygen = 7.0% (wet)
22.5% T.S.

No auxiliary fuel fired

Effect of Auxiliary Fuel Placement

Figure 8: MHF with Varying Auxiliary Fuel Placement

Effect of Auxiliary Fuel Placement
Legends = Wet Cake Capacity, Lbm./Hr.

Oxygen = 6% (wet)
22.5% T.S.

Feed rate adjusted to yield Onset of Combustion at hearth entrance
Auxiliary fuel burners fired on Hearths #1, #3, and #5
Figure 9: Marble-in-Bowl Concept of Stability; MHF = Metastable

Figure 10: Multi-Zone Concept for Fluid Bed Sludge Incinerator
Figure 11: Freeboard Burning in Fluid Bed Sludge Incinerator

Effect of Freeboard Burning on Bed Temperature
No Overfire Air

![Graph showing the effect of freeboard burning on bed temperature.]

Figure 12: Relationship of Freeboard to Bed Temperature

Effect of Raising Freeboard Temperature on Bed Temperature
20% of Total Solids Burned in Freeboard

![Graph showing the relationship of freeboard to bed temperature.]

F. Michael Lewis
fm@earthlink.net
Page 12 of 14
Figure 13: Fluid Bed Sludge Incinerator with Overfire Air

Effect of Overfire Air on Bed Temperature
20% of Dry Solids Burned in Freeboard

Appendix: Brief description of the Hearth by Heath program

The hearth by heath program is extremely complex and was developed over many, many years. The counter-current flow of solids and gases means that whatever happens on one hearth affects each hearth above and below it. A trial and error solution is required. On a PC with a 1 GHz processor, the run time for convergence, after a parameter has been varied, is approximately 10 minutes. Adjusting a parameter so that the Onset of Combustion occurs at the entrance to a hearth requires numerous runs. Generation of a single graph can take a day.

Heat transfer coefficients are calculated for both convection and radiation. When volatiles are burning, an additional modification is made to account for the radiation back down to the bed from the flames. Radiation from burners is not accounted for because they are located on the outer periphery of a hearth where the sludge will be falling through drop holes. Additionally, except for the rare use of oil burners, the burners have essentially non-luminous flames.

The model has been calibrated at several operating furnaces. To account for initial feed distribution and rabbling pattern at different locations, there is a modifier that can be applied to the area of the hearth in question.
References


Lewis, F. M., et al., (1994) Measure Twice Cut Once; A Case History on Upgrading an Operating, 20 Year Old, Multiple Hearth Furnace for the 503’s, Water Environment Federation
