

THERMO-CHEMICAL CONVERSION OF DAIRY WASTE BASED BIOMASS
THROUGH DIRECT FIRING

A Thesis

by

NICHOLAS THOMAS CARLIN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee, Kalyan Annamalai
Committee Members, Warren Heffington
John Sweeten
Head of Department, Dennis O'Neal

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ABSTRACT

Thermo-chemical Conversion of Dairy Waste Based Biomass
through Direct Firing. (December 2005)

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Chair of Advisory Committee: Dr. Kalyan Annamalai

Growing rates of manure produced from large dairies have increased concern for the environmental quality of nearby streams and watersheds. Typically the manure from the freestalls on these dairies is flushed with water to a mechanical separator. Here, flushed dairy biomass (DB) is parted into separated solids and separated liquid. The separated liquid is discharged into lagoons for treatment and eventual land application.

This thesis proposes thermodynamic models for firing DB in small scale boiler systems that would eliminate land application and lagoons, which are being claimed to be the source of nutrient leaching and overloading.

Fuel analysis of flushed DB from a dairy in central Texas show that it contains 93%moisture (%M), 3%ash (%A), and 4%combustibles (%Cb), while separated DB solids contain 81%M, 2%A, and 17%Cb. The dry, ash-free higher heating value of DB is approximately 20,000 kJ/kg. Using dry, ash-free results, computations can be made over ranges of %M and %A. For example, DB containing 70%M requires 9.74%Cb to vaporize all moisture and produce gaseous products of combustion at 373 K, but requires 17.82%Cb to burn in a regenerative combustor with a flame temperature of 1200 K.

Separated solids that are pressed in an auger to 70%M (3%A and 27%Cb) can burn at 1200 K with exhaust temperatures of up to 1130 K and a minimum required heat exchanger effectiveness of 15%. Pressed solids can thus be fired in a boiler, where the remaining separated liquid can be used as feed water. The pressed solids only can release about 30% of the heat required to vaporize the remaining unclean feed water. However, pressed DB solids can be blended with drier fuels to vaporize almost all the unclean water. The low quality steam produced from the unclean water can be used in thermal processes on the farm.

A similar system can be developed for vacuumed DB without the need to vaporize unclean feed water. As for large dairies with anaerobic digester systems already installed, directly firing the produced biogas in a small scale boiler system may be another way to similarly vaporize the remaining effluent.

DEDICATION

To my parents, Patrick and Sylvia Carlin

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Annamalai, for his guidance, and committee members, Dr. Heffington and Dr. Sweeten. I would also like to thank Dr. Mukhtar for serving as a substitute member for Dr. Sweeten during my defense and for arranging the field trip to the Broumley Dairy in Hico, TX.

Thanks to my colleagues Brandon, Paul, Madhu, and Gerardo who work under Dr. Annamalai at the Renewable Energy Lab. Also, I would like to show my appreciation to the Texas Commission on Environmental Quality (TCEQ) for funding the fuel analysis of the dairy biomass samples and to Hazen Research Inc. for conducting the analysis.

With a heavy heart, I would like to express my deepest gratitude to the late Soyuz Priyadarsan for helping me collect the biomass samples at Hico. He was a pleasant and thoughtful young man. I only wish I could have known him better. My sympathies go out to his friends and family.

Finally, thank you to my parents, Patrick and Sylvia, my sister, Annie, and my loving girlfriend, Ann Marie. Thank you for your unending care and support.

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CHAPTER I
INTRODUCTION

Dairy Industry Structure and Trends

The number of dairy operations in the U.S. has declined from 123,700 in 1997 to 97,560 in 2001. However, during this same period the amount of milk produced in the country rose 6% to 165,336 million pounds in 2001. The reason for this seemingly contradictory trend is the increasing number of larger and more efficient dairy operations. As seen in Fig. I.1, the number of operations with more than 500 head of cows increased from 2,336 (29% of all dairies) in 1997 to 2,795 (39% of all dairies) in 2001. The increase in milk cow inventory in larger operations has allowed the U.S. milk production to stay high despite the decline in the overall number of head in the country.

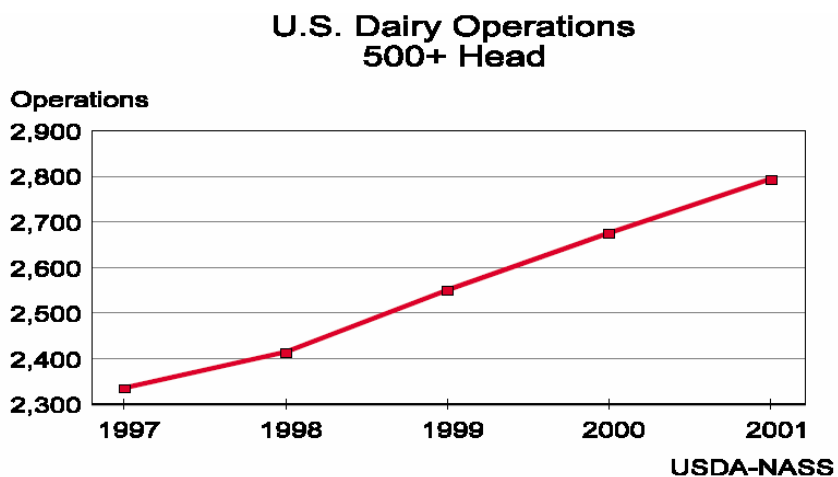


Fig I.1. Number of U.S. dairy operations with over 500 cows. (NASS, 2002)

This thesis follows the style of *Transactions of the ASAE*.

Furthermore, since milk cow inventory has increased in states like California, Idaho, and New Mexico, the amount of production and the number of operations has shifted from the southeast and Midwest to western states. Thus, although Texas lost 53,000 head between 1997 and 2001, it still had 325,000 dairy cows, many of which were milked and kept in larger dairy operations (NASS, 2002).

In the past few years, these trends have continued. The overall number of dairy operations was down to 91,240 in 2002, 86,360 in 2003, and 81,440 in 2004. Yet the expansion in milk output is well established and should continue in 2006 with only modest deceleration (USDA, 2005).

The changes in dairy operation size have increased concerns of water pollution throughout the country because of the growing amount of manure biomass generated from these farms. This has been the case, for example, in the Bosque River Region and Erath County, just north of Waco, Texas. Presently, about 110,000 dairy cattle in over 250 dairies in Erath County produce 1.8 million tons of manure biomass (excreted plus bedding) per year. The dairy cows in this region make up about 25% of the total number of dairy cows in Texas (TX PEER, 1998). The larger production demand on each of the dairies as well as other animal farms has created a greater concentration of animals per farm. Many cattle feedlots, hog farms, and dairies have become confined animal feeding operations (CAFO's) where biomass disposal has become more challenging to the environment. In Fig. I.2, each of the small dots represents an industrial dairy operation located between the Bosque and Leon River Watersheds.



Fig. I.2. CAFO's in north central Texas. (Sierra Club, 2005)

Currently most dairies, as well as other CAFO's, utilize large lagoon areas to store wet animal biomass. Water runoff and land application from these lagoons has been held responsible for the increased concentration of phosphorus and other contaminants in the Bosque River which drains into Lake Waco—the primary source of potable water for Waco's 108,500 people (TX PEER, 1998).

Manure Disposal System Characteristics and Trends

There have been numerous methods—biological and mechanical—developed to reduce the possibility of nutrient leaching and contamination to underground and surface

water sources. In the United States, the most successful of these solutions are those that have also been beneficial to the farmer or owner of the large feeding operation. For example, flushing systems with solid separators or settling basins reduce the overall concentration of nutrients in manure waste streams, making land application of remaining separated liquid from separators more appropriate for irrigation.

Also, common commercial solutions have been simple systems requiring relatively low capital costs and little operation and maintenance time requirements. This is because the responsibility for manure and waste disposal usually falls on the farmer; however, he/she is more concerned with animal breeding, raising, feeding, and ultimately milk and dairy production. Time and energy spent on manure disposal is typically seen as a loss when there is no financial gain or agricultural incentive.

Therefore, technologies like anaerobic digestion, which convert organic solids in the manure to artificial gas, which can then be used to produce electrical power, are installed on farms in some areas of the country because the electricity can be used for heating, running farm equipment, or selling to a utility.

However, anaerobic digesters that produce artificial gas for combustion processes are not main stream, even in the largest dairy producing states (USEPA, 2004). For the current study, these anaerobic digesters are only discussed as comparisons to the proposed models and systems and for reference.

In most cases, government funds or financial assistance from a private engineering or power company must be used to install such systems. Indeed funding for biomass energy systems rose during the energy crisis of the 1970s, but soon dropped off

in the early 1980s when oil prices stabilized. Since the mid-1990s, the interest in digester systems has increased once again due to the emergence of large CAFO's and the possible risks to water sources (Schmidt and Pinapati, 2000). Therefore, the majority of current operational systems were constructed between 1998 and 2002 (USEPA, 2004).

Overall Goal of Research

Anaerobic digesters, as well as other manure processing systems, have not fully addressed the problem of nutrient overloading because nearly all of them continue to require storage lagoons and/or land application. The goal of this research is to develop a system or process that disposes of manure in a way that completely eliminates the need for lagoons and land application and at the same time allows for energy conversion opportunities. The system should also be relatively simple and beneficial to the farmer.

First, dairy farm operations pertaining to manure disposal as well as some energy conversion systems (mostly anaerobic digesters) are reviewed. Next, several proposed waste disposal systems that involve directly firing dairy manure in a combustion chamber are presented and modeled analytically using expressions derived from first principles. The emissions of such systems should include only exhaust gases, dry ash, and steam, thus eliminating the possibility of water pollution. All derivations are presented. After some assumptions and data input, the performance of each of these systems is predicted from the models. Finally, a discussion of results and recommendations for future experimental work and investigation are presented.

CHAPTER II

LITERATURE REVIEW

This chapter first reviews current dairy operations pertaining to manure processing and disposal. Then several energy conversion options currently in use and/or in the research and development phase are discussed.

Typical Dairy Biomass Removal and Processing

Feeder cattle excrete about 28.12 kg of wet manure (88% moisture) per day (Sweeten, 1979). Fig. II.1 depicts the intakes and outputs of a typical 450 kg (992 lb) cow.

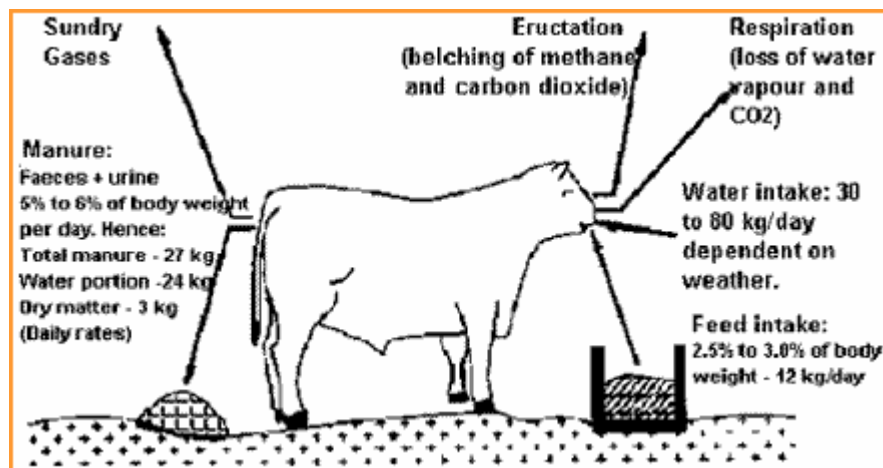


Fig. II.1. Intakes and outputs of a 450 kg cow. (DPI&F, 2003)

Feed intake is about 2.5-3.0% of the body weight while water intake can be 30-80 kg (66-176 lb) per day. The cow's weight gain is only about 1.0-1.6 kg (2.2-3.5 lb) per day; therefore, the rest of the intake must be evacuated. The excreted manure (feces plus urine) amounts to 5-6% of the body weight per day, most of which is water. Some water

is also lost during respiration, while eructation releases some methane and carbon dioxide (DPI&F, 2003).

There are two different types of dairy lots with different disposal procedures: open lots and freestall barns. Open lots (or dry lots) are typically large, rough paved or unpaved areas where cows are allowed to roam freely and sometimes pasture. Manure biomass collected from open lots can be applied as fertilizer, dried by solar heating, or composted. The collection of manure in an open lot usually involves scraping with a tractor or box blade. This process is time consuming and unfortunately allows large amounts of ash to be included with the biomass. Currently there are ongoing improvements to the collection methodology in open lots (DPNM/Agri-Energy, 2005).

In freestall barns (or confined housing), such as the one in Fig. II.2, the dairy cows are kept away from inclement weather in individual stalls with bedding. Much of the time, these freestalls are placed adjacent to smaller open lots where the cows are free to exercise. Manure collection in freestalls may include scraping, but mostly involves flushing systems where water runs downhill over the freestall barn's floor and to a solid separator or settling basin at the end of the barn (Moore and Herndon, 2002; Stokes and Gamroth, 1999).



Fig. II.2. Freestall barn. (Prime, 2005)

Some farmers will use a combination of these two lots. In a hybrid lot, about half of the cows are allowed to pasture all of the time. Another quarter of the cows are kept in freestalls bedded with sand or composted manure, and the remaining 25% are kept in a barn, but are still allowed to roam to the free stalls. Both the freestall and barn are flushed daily with water to remove the manure and soiled bedding (Moore and Herndon, 2002). In Fig. II.3, an aerial view of a hybrid lot along with lagoons and other integral parts of a typical dairy is shown.

Whether a farmer chooses to use an open lot, freestall, or hybrid system depends on a number of factors. Open lots are more suitable for dairies with low animal concentrations in regions with relatively dry weather. Rain and high concentrations of excreted manure create muddy surfaces in the lot. Excessive mud creates maintenance problems for the farmer and lowers the comfort level of the milking cows. Although one tradeoff with freestall barns is that the cows spend more time on concrete barn floors and must be cooled with fans and water sprays during the summer months. Bedding (usually

sand or composted manure) must be applied on a regular basis on the concrete floor to keep the milking cows comfortable, which may increase labor requirements for freestalls (Stokes and Gamroth, 1999).

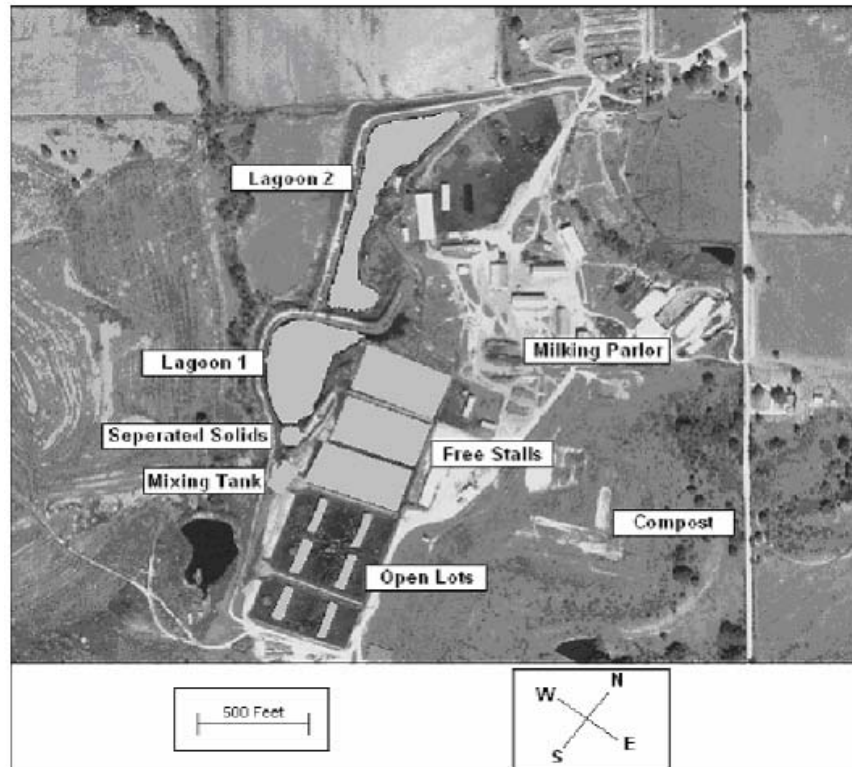


Fig. II.3. Aerial view of a hybrid lot. (Mutlu, Mukhtar, et al., 2004)

Perhaps the largest benefit in using freestalls instead of open lots is saving space. Open lots require 500 to 600 ft² per cow, whereas freestalls typically require only 100 ft² per cow. Therefore, the farmer can keep more milk cows in the same area and produce more milk without having to expand the physical size of the farm. In properly maintained freestalls, dairy cows are more comfortable because they are sheltered from harsh weather and have to walk shorter distances to the milking center (or parlor). One

of the top priorities of any dairy is to keep the animals more comfortable so that they produce greater amounts of higher quality milk (Stokes and Gamroth, 1999).

However, a direct consequence of using freestalls is the need for flushing systems and lagoons. This is because flushing systems are usually automated and decrease the amount of labor required to clean the barn. Since so much labor is put into applying and maintaining bedding, flushing systems are usually a necessity (Stokes and Gamroth, 1999). Although there is less uncontrolled runoff in freestalls and hybrid lots, the flushed manure from these lots may be up to 97% moisture, and must be kept in lagoons. Fig. II.4 is a sketch of typical flushed manure processing on a dairy farm.

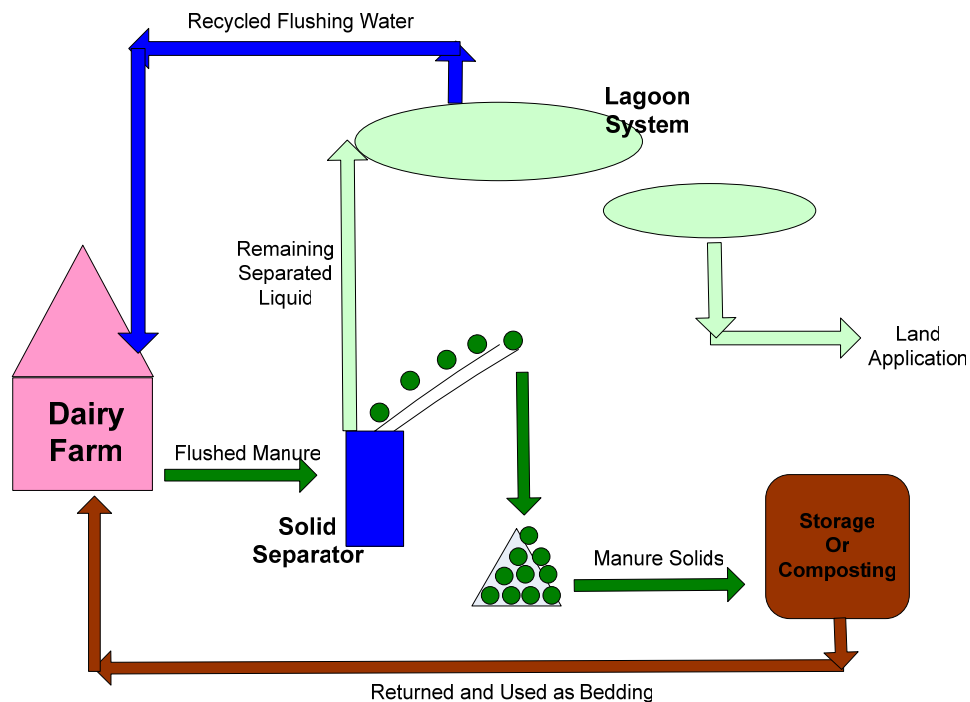


Fig. II.4. Typical processing of flushed dairy manure.

Recently Honey vacuums, such as the one in Fig. II.5, have been used to collect manure in free-stalls without adding more moisture to the fuel. As will be discussed later, higher solid contents in manure streams are beneficial for manure storage, processing, and composting. Honey vacs also reduce flies, odors and water use on the farm. Furthermore, the tank capacity and the suction capability of the vacuum can be sized to meet the requirements of the farm (Matthews, et al., 2003). However, using vacuums in this way is relatively new and few dairies currently have them, therefore most large dairies with freestalls use flushing systems.



Fig. II.5. Honey vacuum. (Broumley, 2005)

The pollution from dairy farms is believed to be caused by the removal and storage of manure. Streams of flushed manure and soiled bedding from the freestalls and hybrid lots as well as runoff from the open lots are typically sent to large lagoons on or near the farm. Dense solids tend to sink to the bottom of the lagoon, which may be up to 20 ft deep. In northern states, straw, dust and other material less dense than water may float to the surface creating a thin crust (Fulhage, 2005). The size of the lagoon

depends on the number of animals on the farm. When a large number of animals are kept in a relatively small area such as a CAFO, problems of lagoon overloading and land overloading begin to take place (TX PEER, 1998). Most lagoons have agricultural lining or clay on the bottom surface to prevent underground water contamination, however, this does not prevent the lagoons from overflowing into nearby streams or rivers during times of heavy rain or overuse.

Solid Separation

At many dairies, solid separators are used to remove some of the heavy solids from the flushed manure streams before they enter the lagoons. This makes the draining process easier because the pumps have to handle fewer solids in the slurry. Separation also cuts odors in the lagoon, reduces localized build-up of solids, lowers the frequency of required drainage, and reduces the possibility of pollution. Much of the pollutants such as phosphorus are in the solids, and removing them makes the water in the lagoons safer for the environment (Mukhtar, Sweeten and Auvermann, 1999).

There are several types of separators; each performs differently depending on the size of the operation and the type of manure being treated. Commonly large dairy farms will have settling basins, designed to remove solids from the manure stream by sedimentation. Retention times for the manure are usually 20 to 30 minutes. However, it has been shown that screen separators are best suited for manures with less than 5% solids such as flushed manure from hybrid operations. An in-channel flighted conveyor screen, for example, drags flighted conveyors carrying liquid manure over an inclined screen. Solids remain on the conveyors while moisture drains through the screen.

Efficiencies vary widely for screen separators between 3 and 67% of total solids removed (Mukhtar, Sweeten and Auvermann, 1999). An example of a screen solid separator is shown in Fig. II.6.

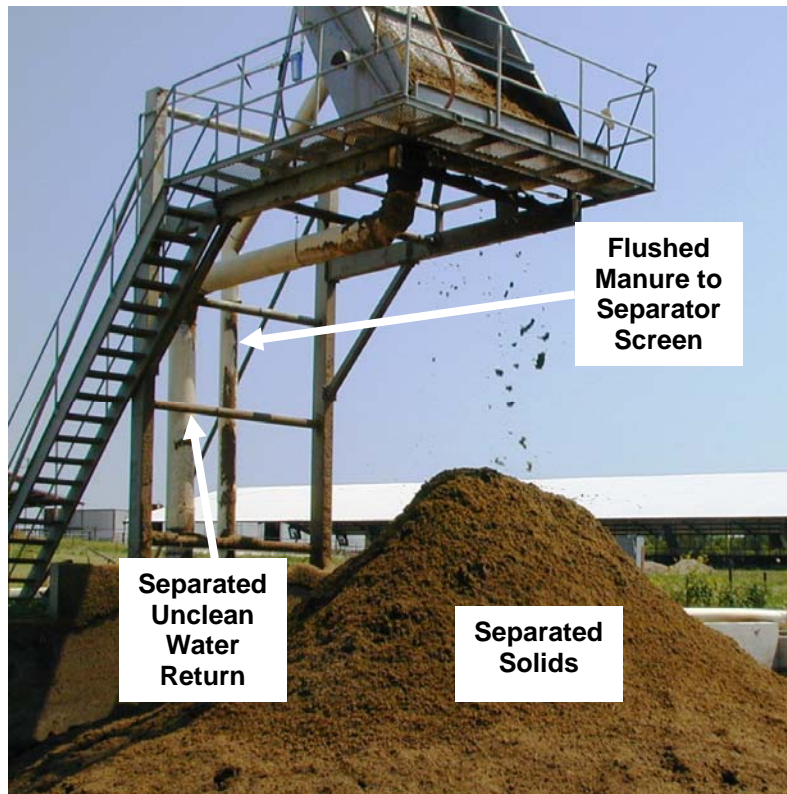


Fig. II.6. Screen solid separator. (Broumley, 2005)

Sometimes, down stream from the screen separator, presses will remove additional moisture from the removed solids. In a study by Young and Pian (2003), a commercial auger press was used to reduce 4.5-45 m³/hr of removed solids to 70% moisture. A schematic of the auger press is depicted in Fig. II.7. This press uses a screw-type conveyor to remove the solids retained from a cylindrical screen. The

moisture is squeezed out from the solids like water from a sponge. Some presses and augers can reduce the moisture in DB even without a screen solid separator.

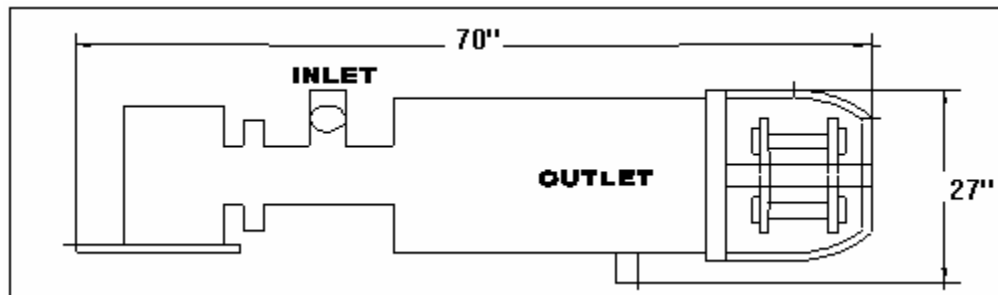


Fig. II.7. Screw/auger press. (Slegers, 2000)

Performance and specifications of this auger press can be found in (Slegers, 2000). The removed solids are usually composted or used as fertilizer, while the remaining liquid is sent to a lagoon. The liquid stream may have 1 to 6% solids remaining even after the separation processes. Some of the remaining liquid may be re-used to flush the freestall barn.

Lagoon Management and Use

Lagoons are used to store and treat high moisture agricultural manure waste. In cases in which a solid separator is used, the high moisture stream of remaining separated liquid is stored and treated in the lagoon. The volatile solids in the stream are diluted in the water and are broken down by anaerobic biological processes. These processes are discussed in slightly more detail in the anaerobic digester section below. The speed and efficiency of the biological processes depends greatly on ambient temperature, pH in the lagoon, and the general management of the lagoon. Other inorganic material in the

manure stream such as sand and minerals are not broken down by the biological processes and instead, settle to the bottom of the lagoon and create a layer of sludge (Mukhtar, 1999).

Lagoon systems are usually made up of stages or cells. The first stage will contain most of the sludge build up on its floor, while overflow will spill into the second, third and subsequent stages. Different farms use varying numbers of stages (usually two or three). The liquid in the final stage will contain relatively little inorganic material, although soluble substances such as phosphates and nitrates will still be present. A study of the nutrient content in lagoon water can be found in (Mukhtar, Ullman, et al., 2004). The liquid in the final lagoon stage is used for irrigation or as recycled flushing water (Mukhtar, 1999).

The critical part of managing a lagoon or a lagoon system is to control what goes into it. Reducing the amount of inorganic material that enters the lagoon lessens the amount of sludge build up and hence prolongs the life of the lagoon. It is also critical that a balance between loading and the reaction time of the biological processes is achieved. For this reason, management during the first year after the lagoon is built is important (Mukhtar, 1999).

Lagoon Draining

However, if there is too much sludge build up in the lagoon, then the settled solids must be removed. Once or twice a year, depending on loading and the practices of the farmer, the lagoons are agitated and drained and the inorganic solids are applied to the land. Although the drainage process varies, it usually involves a propeller-type

agitator driven by a 100 to 150 hp tractor which suspends the settled solids and breaks up any crust on the surface (Fig. II.8a). Ideally, the agitator should create a swirling effect so that solids and crust travel to the propeller blades to be chopped and mixed with the water to form slurry (Fulhage, 2005).

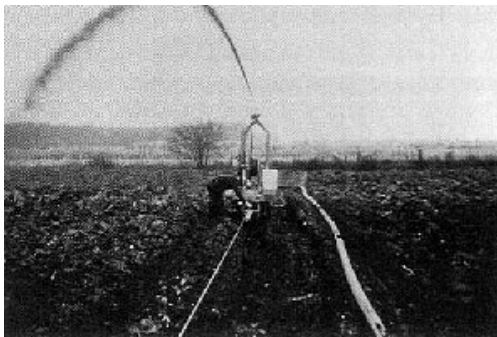
Next, a chopper pump further fragments the solids to prevent plugging in the piping. The pump may be submerged in the water or floating on the surface. Typically a bypass valve allows for further agitation near the pump. Most chopper pumps deliver about 500 gpm of slurry at 15 to 20 ft head. A booster pump provides 100 to 140 psi of extra pressure to send the slurry to the farmland for distribution (Fig. II.8b).



(a)



(b)



(c)



(d)

Fig. II.8. (a) Propeller-type agitator (b) Booster pump fed by a submerged chopper pump (c) Traveling gun applicator (d) Injection applicator installed on a tractor. (Fulhage, 2005)

The slurry travels through conventional aluminum irrigation piping or buried PVC pipes to a traveling gun applicator. The applicator distributes the slurry evenly over the land (Fig. II.8c). Sometimes instead of a gun applicator, an injection applicator installed behind a tractor (Fig. II.8d), places the slurry under cultivated soil to reduce malodorous odors and nutrient losses (Fulhage, 2005).

This operation usually works well, however, as the size of dairy operations increase there is greater danger of sludge build up in the lagoons. Sometimes there is simply not enough land to distribute all of the nutrients and minerals from the manure and the soil becomes overloaded (Johnson, Culkin, and Stowell, 2004). In such cases, phosphorus and other contaminants from the manure erode to nearby water sources.

Nutrient Overloading on Farmland

Usually applying the lagoon liquid to farmland has few consequences to down gradient water sources. The bacteria found in the liquid are typically non-threatening to groundwater sources because they are restrained by filtration. Furthermore, sunlight and dry weather tend to kill much of the bacteria applied to the ground. However, the nutrients in the manure (phosphates, nitrates, etc) can leach to groundwater when soil and plants do not fully absorb them, particularly in times of heavy rainfall (Ahsanuzzaman, Zaman, and Kolar, 2004).

However, other factors such as the properties of the soil and the type of crops on the land can also play a large role in ground water leaching from manure streams. A simple expert system developed by Ahsanuzzaman, Zaman, and Kolar, (2004) can estimate nutrient travel distances given “simple” input conditions that are readily

attainable at the CAFO and neighboring water source. The system is a fairly intricate set of equations derived from basic principles and managed in a database. Although similar systems have been developed for other environmental risks, this system is one of the first to concentrate on manure land application and groundwater pollution.

Specifically, for dairies a rule of thumb to prevent water pollution is to own about 2 cows per acre to safely apply the lagoon liquid to the land. According to Borba Dairies in Chino, California this ratio is precisely 2.71 cows per acre; however the exact number tends to vary due to some of the factors just mentioned. Also, the animals on the farm are typically counted in “animal units” (AU’s). For example a full grown milk cow is 1.0 AU while a young calf is only counted as 0.35 AU. The species of dairy cow is also taken into account. For instance the number of Holsteins is multiplied by 1.4 during counting (Project Clean Air, 2000).

Despite this caution to avoid nutrient overloading, growing herd sizes make it difficult to maintain necessary animal to acreage ratios. Consequently, many farmers must move their operations to other sites with more land. It is expected that an alternative waste management system that fully eliminates the practice of applying manure to the land will save farmers from the need to relocate.

Anaerobic Digestion

Currently, several technologies—both in the R&D phase and commercially available—have shown promise in disposing agricultural waste and, at the same time, generating energy. In the United States, the most popular of these is anaerobic digestion. Raw manure enters a chamber at a designed temperature and is allowed to decompose.

The manure sits in the chamber long enough for bacteria to convert the combustible material into biogas. The biogas contains 55-75% methane (CH_4), with the balance of carbon dioxide (CO_2) and hydrogen sulfide (H_2S) (Schmidt and Pinapati, 2000).

The actual biological process of anaerobic digestion contains two steps. First the complex carbohydrates (starches, sugars, proteins, and fats, commonly referred to as volatile solids) are broken down into volatile fatty acids and amino acids by microorganisms called fermentive bacteria that thrive in the zero oxygen environments in the digestion chamber. Furthermore, acetogenic bacteria convert products from the fermentive bacteria to form simple organic acids, carbon dioxide and hydrogen. This step is typically called hydrolysis. The second step is called methanogenesis and occurs when methane producing bacteria consume the acids and release CH_4 and CO_2 . The primary methane producing reaction is called the acetate reaction (Johnson, Culkin, and Stowell, 2004; Monnet, 2003). Similar biological processes occur in anaerobic lagoons discussed above.

The time required for the microorganisms and bacteria to decompose the manure is called the hydraulic retention time. If the digester is designed properly, the process of converting animal manure into biogas should become steady, allowing a fixed flow of available biogas for a combustion process. Currently, almost all commercial anaerobic digester systems use industrial natural gas IC engines to generate power. These engines have been successful since the biogas does not need to be treated before firing. Systems that employ boiler burners, gas turbines, sterling engines, and fuel cells are all in the R&D phase (Schmidt and Pinapati, 2000).

Basically, there are three types of anaerobic digesters used for dairy manure streams: covered lagoon digesters, mix digesters, and plug flow digesters. The main difference between them is the hydraulic retention time. Lagoon digesters require high retention times—40 to 60 days—because they are not externally heated, and are therefore found in warmer climates in the southeast and southwest. Whereas, mix and plug flow digesters are usually heated by exhaust from the IC engine, requiring retention times of only 15 days. This makes them suitable for cooler climates. However, mix digesters have high operation and maintenance costs due to solids settling in their steel or concrete chambers. Plug flow digesters operate the same way as mix digesters, except that they are designed to minimize these costs. The plug flow chambers are usually partially underground pits suitable for dairy manure but not hog manure (Schmidt and Pinapati, 2000).

However, as was mentioned before, systems that actually capture biogas from anaerobic digesters on farms are not common in the United States. There are only 40 operational systems in this country, 29 of which are on dairy farms. Thirty-five of these systems burn the biogas to generate electricity while the others use simple flares to burn the biogas to control odor. The states with the most operational systems are California (7), Iowa (5), New York (5), Pennsylvania (5), and Wisconsin (5). Texas does not have an operational digester system as of June 2004 (USEPA, 2004).

Although there may not be much difference between the way each plug flow digester or each covered lagoon digester works, the ways that the manure is collected and prepared for the digestion chamber, as well as the way the outgoing effluent is

processed or stored, differ for each system. The system setup usually depends on the dairy farm's layout and the practices of the particular farmer. It would be impractical to review all the ways a digester system could be set up; therefore, the following will discuss an example of a covered lagoon digester system and another example of a plug flow digester system. Some of the handling practices in these two examples may be relevant to the proposed systems in the next few chapters. Furthermore, studying these systems may give some sense to the amount of energy (electrical or thermal) that can be currently produced from dairy waste.

Example of a Covered Lagoon Digester System

The covered lagoon digester system discussed presently is a pilot system installed (but not yet operational) on the Keith Broumley Dairy near Hico, Texas. It is also the only digester currently built in the Bosque River Region. The installation was completed in early June 2005. A diagram of the digester system can be seen in Fig. II.9. The Broumley Dairy is a 900 head Jersey cow operation, which uses a flush system in the stalls. The stalls are built on a slope so that the flush water runs down gradient to a screen separator.

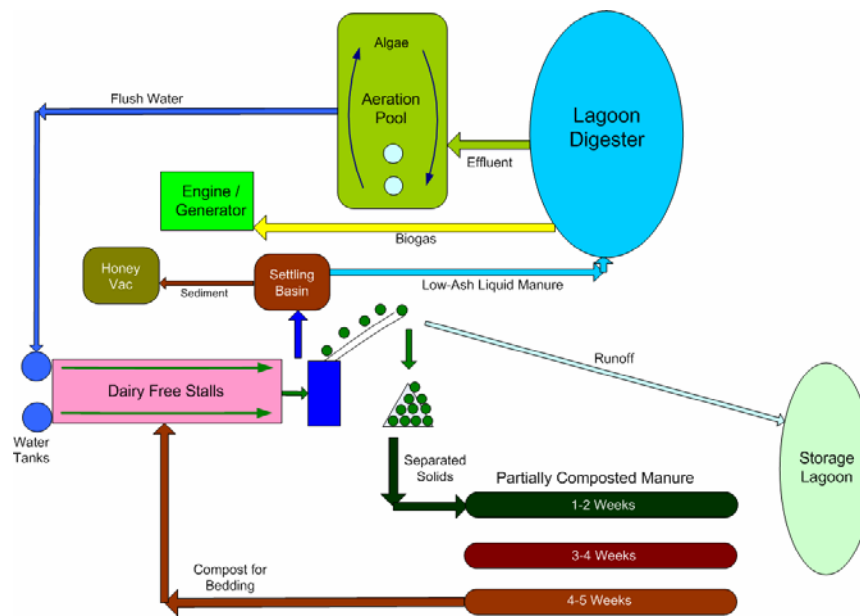


Fig. II.9. Covered lagoon digester system. (Broumley, 2005)

The solids are partially composted in windrows near the separator and used as bedding, while the separated liquid drains into a small settling basin. The purpose of the settling basin is to allow as much of the ash and inorganic material as possible to settle to the ground while a pump on the surface sends the liquid manure to the covered lagoon digester (Broumley, 2005).

The liquid manure that enters the covered lagoon has a very low solid content, much of which is volatile solids. This ensures that most of the carbon (C), hydrogen (H), and oxygen (O) in the complex carbohydrates entering the digester are converted to either CH_4 or CO_2 , and that the hydraulic retention time is as short as possible. Ventilation tubes protrude up from the lagoon cover to allow CH_4 to escape in case the engine and flare fail or are down for maintenance.

The effluent from the digester is sent to an aeration pool right next the lagoon digester (Fig. II.10). On one side of the pool, two fountain-like aerators transport the effluent from the low oxygen environment in the digester up to the surface of the pool and turbulently mix it with the atmospheric air. This reduces the odor of the effluent and makes it available for reuse as flushing water. On the other side of the pool, algae grow in the effluent and reduce the amount of phosphorus. The effluent slowly circulates from one side of the pool to the other so that all of it is fully aerated and relatively free of phosphorus. The effluent is then sent to water tanks at the far end of the stalls and reused as flushing water (Broumley, 2005).



Fig. II.10. Aeration pool. (Broumley, 2005)

The biogas is collected in a pipe that circles around the digester and ends at an engine room about 30 feet from the aeration pool and digester. As of July 2005, the IC

engine was not yet in operation at the Broumley Dairy. A small flare next to the engine room was burning the biogas while the engine was down. It is estimated that the system will produce 76 kW of power when the digester produces the biogas at the designed rate and the IC engine is in full operation (Broumley, 2005).

However, there is still a regular, uncovered lagoon located about 100 yards down hill from the solid separator that is used for irrigation. This lagoon is only used when the covered lagoon digester is at full capacity and when runoff washes solids downhill during times of heavy rainfall. Also, a Honey Vac is used periodically to clean up any inorganic material collected in the settling basin (Broumley, 2005).

A problem found in anaerobic digesters, particularly covered lagoon digesters, is odor. The methane producing bacteria can only live in a certain pH range. The ideal pH range for methanogenesis is between 6.6 and 7 (Monnet, 2003). If the pH becomes too high or too low, the methane producing bacteria die while the other microorganisms remain alive. Therefore only the first step in anaerobic digestion is completed and the effluent becomes contaminated with volatile fatty acids which can become airborne and cause odor (Johnson, Culkin, and Stowell, 2004). It may take about a year for the pH level in the covered lagoon to optimize. When it does, the methane producing bacteria bloom and optimum amounts of biogas are produced.

Example of a Plug Flow Digester System

A plug flow digester system was completed in the spring of 2002 on the Top Deck Dairy owned by Roger Decker in Westgate, Iowa. A complete description of the facility can be found in (Meyer, 2003). A diagram of the digester system can be seen in

Fig. II.11. Raw, manure is sent to a tank which is heated to 98°F by hot water from the engine/turbine room.

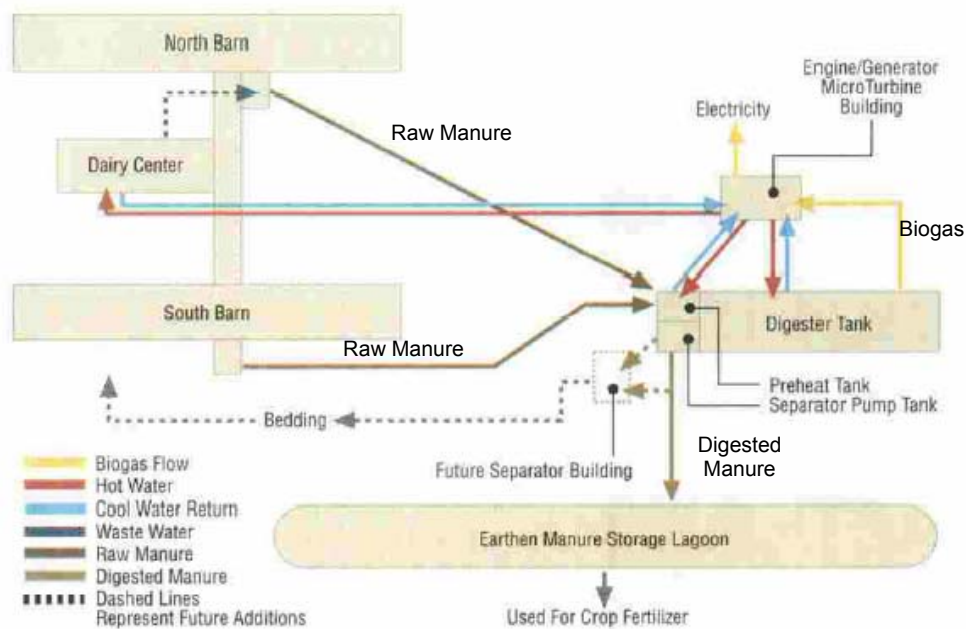


Fig. II.11. Plug flow digester system. (Meyer, 2003)

This preheat tank also acts as a settling basin to remove inorganic material, similar to the one for the covered lagoon. The preheated manure is then pumped into a 40,176 ft³ closed concrete digester tank, partially underground. The hydraulic retention time is about 14 days based on 29 gallons of manure per cow per day. The digested effluent flows by gravity into a separator pit and then to a separator. Again, much like the previous system, the solids are used for bedding in the barns, however, the liquid manure is sent to an open storage lagoon.

Notice how in this case, unlike the covered lagoon digester system, the solid separator is used after digestion. This is because covered lagoon digesters are only capable of processing manure with up to 3% solids and must have solids removed before hand. However, plug flow digesters, such as this one, can process manure with up to 10% solids and hence generate more CH_4 because preheating speeds up the biological processes during the digestion (Schmidt and Pinapati, 2000).

Indeed, the biogas produced from the plug flow digester and fired in the micro turbine and the IC engine in this example produces 100 kW of electrical power and peaks at 125 kW for a 700 head farm. The previous example of a covered lagoon digester on a 900 head farm is expected to only produce 76 kW of power. However, the biogas from the plug flow digester needs to be cleaned, compressed and dried before entering the micro turbine's combustion chamber. Also, plug flow digesters are more difficult to maintain and installation is typically more expensive than a covered lagoon system. For example, there were problems with maintaining the pressure in the plug flow digester tank because the H_2S in the biogas deteriorated the concrete. Polyurea spray sealant had to be applied to the inside walls of the tank in contact with the biogas costing \$4 per ft^2 .

High-temperature, Air-blown Gasification

Manure energy conversion systems such as the previous two digester systems are the most commercially available because they are relatively inexpensive and can, for the most part, be maintained by the farmer and his farm hands. However, there are some technologies that are vastly more complicated and expensive—yet more efficient—in the

research and pilot stages. One example of these is the MEET (Multistaged Enthalpy Extraction Technology) gasification system discussed in (Young and Pian, 2003).

The moisture in the dairy manure is first reduced to about 70% with an auger press. The remaining liquid manure is land applied or stored in a lagoon while the solid manure (30% solid) is sent through the gasification system. In a pebble-bed gasifier vessel, high-temperature air and solid manure are mixed in an entrained-flow section where the manure is heated to 1830 °F at a rate of 220 °F per second. This process results in hot liquid slag and syngas (synthetic gas) made up of CO, H₂, and N₂. Particulates are removed by a ceramic pebble-bed filter. The syngas is further cleaned in an aerodynamic module with a ring cone assembly.

The most advanced portion of this system is the high-temperature air preheater (Fig. II.12). Heat is alternately stored and removed in honeycomb heat storage beds as small amounts of the syngas are fired with ambient air. When the flow alternates, the heated bed cools as air flows through it to become high temperature air for the gasifier. At the same time, an identical combustor fires a small amount of syngas to reheat the other storage bed, and the cycle continues as the air flow is alternated back.

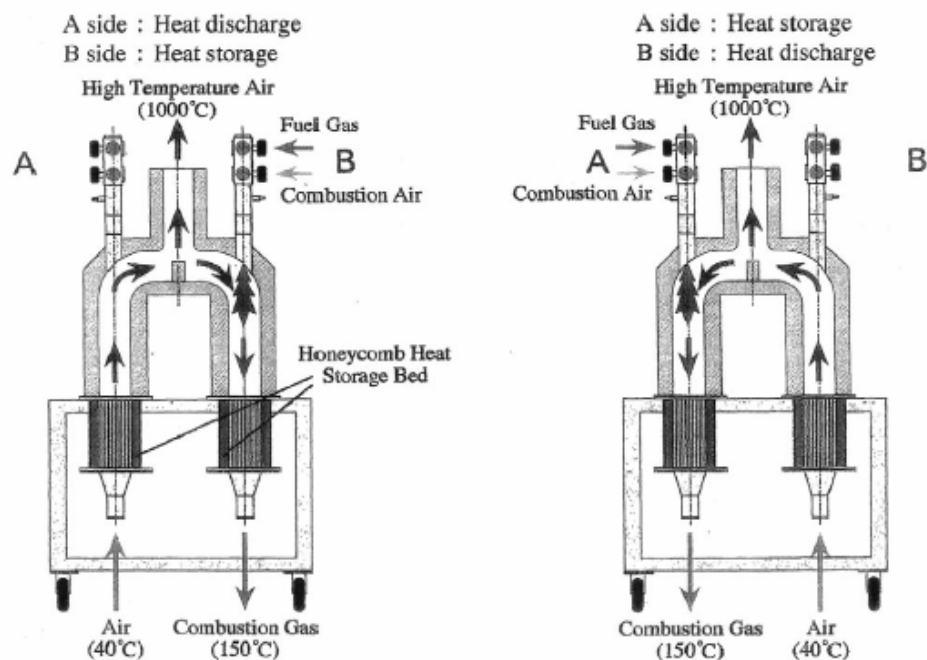


Fig. II.12. Operating principle of the high-temperature air preheater. (Young and Pian, 2003)

This system boasts gasification efficiencies of 65 to 85%. In a case study of this system (on the Sun Rich Farms in Albion, New York—about 420 head), the syngas produced allowed the farm to exceed energy self-sufficiency by over two times its requirements (Young and Pian, 2003)!

However, the author of the study does admit that most dairy farmers could not purchase such a system alone. Partnerships with energy companies or other outside groups would certainly be required to cover the capital cost as well as the maintenance of such a system (Young and Pian, 2003). Also, the MEET gasification system does not address the original problem discussed earlier in this chapter, and that is the overloading of nutrients on farmland from land applied liquid manure and irrigation water from treatment lagoons.

However, this argument can be extended to the simpler anaerobic digestion systems as well. There is nothing about digesters or gasifiers that fully eliminate the need for lagoons and land application. Even when effluent is aerated and reused as flush water, inorganic species like phosphorus and potassium can still accumulate in the system and eventually must be removed (Johnson, Culkin, and Stowell, 2004), although biological solutions such as the algae in the covered lagoon example do help the problem to an extent.

Manure Wastewater Filtration

Furthermore, there are some exotic mechanical solutions that have shown promise in reducing the amount of inorganic species in manure streams and effluent. One of these is the VSEP (vibratory shear enhanced process) RO (reverse osmosis) Filtration System developed by New Logic Research, Inc., discussed in (Johnson, Culkin, and Stowell, 2004). Such filtration systems have been used to treat wastewater in the past, and only recently have been applied to animal manure in Korea and Japan.

The filtration system can be used to treat flushed manure right out of the stalls, or it can be used in conjunction with a digester system to pre-treat manure going into the chamber, or more commonly, to treat effluent exiting the digester.

Reverse Osmosis membranes can filter all particles in the waste greater than 0.001 microns. However, the filtration process can be time consuming due to colloidal fouling and polarization of the membrane. The VSEP system remedies this problem by vibrating the membrane creating sinusoidal shear waves that suspend the collected solids

above the membrane's surface. This allows a greater rate of clean water to go through the filter (Johnson, Culkin, and Stowell, 2004).

Vibratory reverse osmosis membranes have reductions of 98.1% for phosphorus and 98.9% for potassium. There are also other methods of treating wastewater, but a VSEP RO system seems to perform well for all types of material in wastewater. For example, sequencing batch reactors remove suspended solids and chemical oxygen but only remove 60% of the nitrogen and 15% of the phosphorus. Tangential flow separators remove 90% of phosphorus but only 22% of nitrogen and actually add 210% chlorides and 60% calcium (Johnson, Culkin, and Stowell, 2004).

Aerobic Digestion

Aerobic digestion occurs in a number of steps, each in separate tanks. First there is filling, then aeration, reaction time, settling, drawing down, and finally idling. The process is very slow and requires huge tanks that would be impractical to construct on most any farm, although Sequence Batch Reactors are aerobic digesters that only use one tank to perform all six steps in the process (Johnson, Culkin, and Stowell, 2004).

Like anaerobic digestion, bacteria are used to break down the organic matter in the manure, except that these bacteria live off of oxygen and convert the volatile solids into CO_2 , H_2O , and ammonia (NH_3). Further processes are used to break down the NH_3 into nitrates (Johnson, Culkin, and Stowell, 2004). Yet, basically aerobic digestion converts 40% of the manure wastes to more solids, requiring further waste disposal, whereas, anaerobic digestion is faster and converts only 4% of the waste to more solids (Schmidt and Pinapati, 2000). Plus, there are no opportunities for energy production

with aerobic digestion alone. Hence, aerobic digestion is usually limited to processing waste water streams and sludges. As far as energy conversion, agricultural manure wastes are almost exclusively processed by anaerobic digestion or gasification.

Incineration

However, a relatively new technology developed by Skill Associates, Inc. called Elimanure™, claims to eliminate both the liquid and solids of any animal manure. Waste manure up to 95% moisture enters large drying units and is mixed by giant augers with hot air. The temperature in the drying units reach 160 °F and the manure is dried to about 40% moisture. The water vapor is ventilated out of the drying unit, while the 40% moisture solid manure is sent to a thermal gasification boiler where it is burned at 2000 °F. The boiler generates steam which runs turbines to generate electricity (Skill Associates, 2005).

During the first two hours of operation, the system uses propane or some other fuel to start up, but after that, the dried manure can sustain the process. Besides water vapor from the drying process, the only byproduct is a grey powdery ash which contains the inorganic or noncombustible material in the manure. A new facility with this incineration system will be built in Greenleaf, Wisconsin in 2005 (Skill Associates, 2005).

Such an incineration system does seem to answer the problems discussed earlier in this chapter; however, the equipment used, particularly the giant augers in the drying unit would probably also be expensive. Indeed, there is no mention of cost in (Skill Associates, 2005). Also, it is not clear how much maintenance will be required for such

large systems. It seems that an incineration system would be suitable only for the largest CAFO's.

The proposed waste management systems discussed in the next few chapters similarly directly burn waste manure streams only without the need for drying and presumably without extra fossil fuels such as propane. This should make the needed equipment smaller and more accessible to small and mid-sized dairies (< 1,000 cows).

CHAPTER III

OBJECTIVE AND TASKS

This study investigates the possibility of generating heat from combusting dairy biomass (DB) or separated dairy biomass solids. The heat is then to be used for vaporizing the moisture in the remaining separated liquid (referred to as unclean water in the next two chapters). The primary objective is to develop and analyze a set of processes in which separated solid manure, remaining separated liquid, and air enter the combustion system and gaseous combustion products, ash, and relatively pure liquid water exit the system. Such a system would thus eliminate the need for land application and storage lagoons on dairy farms, and may also result in the production of electrical or thermal power generation. The tasks performed to accomplish the objective are as follows:

1. Conduct fuel analysis of DB in order to determine its reliability as a fuel,
2. Derive equations from first principles that can thermodynamically model biomass combustion systems with DB as fuel, and
3. Using the performance results of the analytical models, determine which scheme best satisfies the objective.

CHAPTER IV

MODELING

The first section of this chapter will discuss how dairy biomass (DB) can be modeled as a fuel. Next, general equations for five models will be derived from first principles. The models are: (I) direct combustion of DB, (II) regenerative combustion systems, (III) vaporizing moisture from flushed manure in a fire-tube boiler, (IV) disposal system for vacuumed dairy manure, and (V) combined digestion and firing system. Note that all equations will be derived in SI units (kilogram (kg), meter (m), second (s), and Kelvin (K)), unless otherwise specified.

Modeling Dairy Biomass

The content of DB, as well as most other biomass fuels, varies greatly for a number of reasons. As excreted, DB typically has a moisture content of about 88%. However, since plenty of bedding (about 12 lbs of bedding per 100 lbs of excreted DB) is also present in the dairy stalls, the moisture content of dairy manure on the ground in a free stall is usually lower (Fulhage, 2005). Nevertheless, depending on how the biomass is collected and how long it is stored, the ash and moisture contents can be very different. For example feedlot biomass (FB), which is scraped from the ground, can have ash percentages of 20 to 50% (Sweeten and Annamalai, 2003). Yet, flushed dairy biomass from a free-stall can have much less ash and up to 96% moisture. Furthermore, solid separators and settling basins can each change moisture and ash contents to different degrees. Also, many of these systems are located outdoors where rain or dry weather can change moisture content dramatically. Therefore, it is difficult to say how

much moisture and ash is in a manure stream at any given time. Hence, the moisture and ash percentage, $%M$ and $%A$, will typically be treated as variables in the following equations so that calculations can be made for a range of moisture and ash contents.

In Chapter II, DB was said to be made up of complex carbohydrates commonly referred to as volatile solids or volatile matter. However, for making combustion calculations one does not need to know the chemical formulas and the amount of each of these carbohydrates. A simple empirical formula containing the total amount of elements—carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S)—in the fuel is enough to perform atom balances of all the material in the DB fuel and estimate adiabatic flame temperatures and thermal outputs in combustion processes. This empirical formula can be derived from an ultimate analysis of the biomass fuel. Therefore, in the context of combustion problems, one can think of biomass as containing three materials: combustibles, moisture, and ash (Annamalai and Puri, 2004).

The basis for modeling DB in combustion systems comes from the fact that the combustible composition of all cattle biomass is virtually the same despite the ash and moisture percentages. It may be assumed, to a fairly good approximation, that the dry, ash free (DAF) combustible content does not change as $%M$ and $%A$ vary; although, it is hypothesized that some solid separators capture C , H , and O more efficiently than N and S because particles of complex carbohydrates are typically larger than some particles containing N and S . However, for the present calculations it can be assumed that the DAF numbers are a characterization of a particular animal biomass. One only needs the

DAF composition of the combustibles to make calculations over a range of moisture and ash percentages.

The amount of each element C , H , N , O , and S in the combustibles on an as received basis can be expressed in terms of $\%M$, $\%A$, and the dry, ash free content, DAF_k .

$$\begin{aligned}
 C & \left[\frac{\text{kmol } C}{100 \text{ kg of as received DB}} \right] = \frac{(100 - \%M - \%A) * DAF_C}{12.01} \\
 H & = \frac{(100 - \%M - \%A) * DAF_H}{1.008} \\
 N & = \frac{(100 - \%M - \%A) * DAF_N}{14.0067} \\
 O & = \frac{(100 - \%M - \%A) * DAF_O}{15.997} \\
 S & = \frac{(100 - \%M - \%A) * DAF_S}{32.064}
 \end{aligned} \tag{IV.1}$$

The constants in the denominators are the molecular weights of respective elements. Using equation (IV.1) as a model for the DB fuel, one can now proceed with the combustion analysis.

Model I: Direct Combustion of Dairy Biomass

a) Mass/Atom Balance

First, consider the most general case for a combustion process in which DB fuel is directly fired with air (assumed dry, with 79% N_2 and 21% O_2) to produce products of combustion (CO_2 , H_2O , N_2 , and SO_2 along with ash which is assumed to be inert). This case is shown graphically as a control volume problem (CV) in Fig. IV.1.

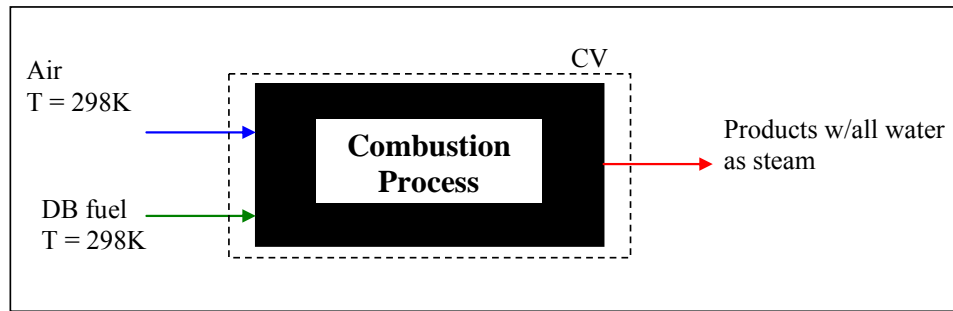
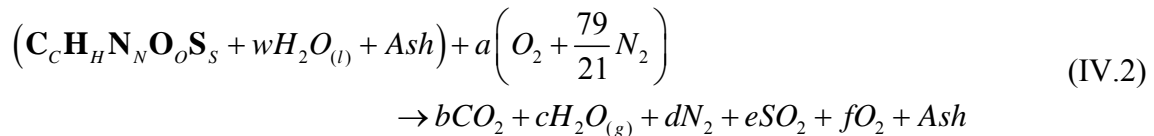


Fig. IV.1. General combustion process.

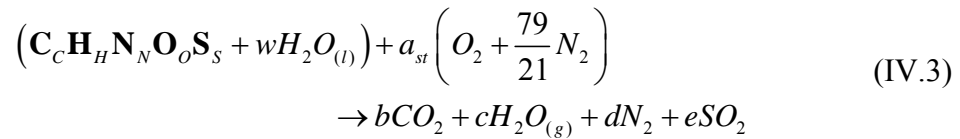
Suppose 100 kg of DB fuel enters the CV and is fired. The combustible contents in equation (IV.1) can be used in balancing each element during the combustion process. Thus one can write the following general chemical reaction equation for reactants and products entering and leaving the CV.



Note that in this study, complete combustion is always assumed. Here, w is the number of kmoles of liquid water per 100 kg of as received fuel. The unknowns in this reaction are a , b , c , d , e , and f . Since it is assumed that all the moisture will be vaporized, c at the end of the reaction includes the moisture in the fuel plus any water created during the combustion. Also, it is difficult to know the molecular weight of the ash, since there are a number of species that form it. However, since the components in the ash are assumed to be inert, ash is left on a mass basis and balanced separately. Its inclusion in equation (IV.2) is merely for completeness.

The goal is to solve this equation for the number of kmoles of each species coming in and going out of the CV in terms of the combustibles in the fuel and the

amount of excess air entering the CV. Before solving this chemical equation, one should notice that O_2 appears in the products. In a combustion process, an excessive amount of air will cause this extra term to appear on the right hand side. Therefore, to solve equation (IV.2), one must first consider the following stoichiometric reaction, in which an ideal amount of air is used in the combustion process.



The atom balances of (IV.3) are now conducted.

Carbon:

$$b = C \quad (IV.4)$$

Hydrogen:

$$c = \frac{H}{2} + w \quad (IV.5)$$

Sulfur:

$$e = S \quad (IV.6)$$

Oxygen:

$$O + w + 2a_{st} = 2b + c + 2e$$

$$a_{st} = C + \frac{H}{4} + S - \frac{O}{2} \quad (IV.7)$$

The variable a_{st} is typically called the stoichiometric oxygen-fuel ratio, whereas a in equation (IV.2) is simply the oxygen-fuel ratio. The relation of these two variables is the percent excess air (or excess oxygen), %EA, conveyed in the following equation.

$$\%EA = \left(\frac{a}{a_{st}} - 1 \right) * 100 \quad (IV.8)$$

Solving (IV.8) for a and plugging in (IV.7) for a_{st} , one can obtain the following equation for the oxygen-fuel ratio in terms of the biomass fuel's combustible components and the percent excess air.

$$a = \left(\frac{\%EA}{100} + 1 \right) \left(C + \frac{H}{4} + S - \frac{O}{2} \right) \quad (IV.9)$$

The atom balance for (IV.2) can now be completed, keeping in mind that b , c and e are the same as in equations (IV.4), (IV.5), and (IV.6).

Oxygen:

$$O + w + 2a = 2b + c + 2e + 2f$$

$$f = \frac{\%EA}{100} \left(C + \frac{H}{4} + S - \frac{O}{2} \right) \quad (IV.10)$$

Nitrogen:

$$N + 2a \left(\frac{79}{21} \right) = 2d$$

$$d = \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) \left(C + \frac{H}{4} + S - \frac{O}{2} \right) + \frac{N}{2} \quad (IV.11)$$

With equations (IV.4) through (IV.6) and (IV.9) through (IV.11), the number of kmoles of each species, N_k , entering and leaving the CV can be written as:

$$\begin{aligned}
N_{DB,DAF,in} &= 1, \\
N_{O_2,in} &= \left(\frac{\%EA}{100} + 1 \right) \left(C + \frac{H}{4} + S - \frac{O}{2} \right), \\
N_{N_2,in} &= \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) \left(C + \frac{H}{4} + S - \frac{O}{2} \right), \\
N_{CO_2,out} &= C, \\
N_{H_2O_{(g)},out} &= \frac{H}{2} + w, \\
N_{N_2,out} &= \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) \left(C + \frac{H}{4} + S - \frac{O}{2} \right) + \frac{N}{2}, \\
N_{SO_2,out} &= S, \quad \text{and} \\
N_{O_2,out} &= \frac{\%EA}{100} \left(C + \frac{H}{4} + S - \frac{O}{2} \right).
\end{aligned} \tag{IV.12}$$

Note that the O_2 and N_2 into the control volume are parts of the combustion air. Also, the kmoles of liquid moisture, w , and the mass of the ash, m_{ash} , in the chemical reaction equation (IV.2) can be expressed in terms of $\%M$ and $\%A$, respectively.

$$w = \frac{\%M}{18.02}, \quad m_{ash} = \%A \tag{IV.13}$$

Plugging (IV.1) and (IV.13) into (IV.12), one can obtain the kmoles of each species entering and leaving the CV in Fig. IV.1 in terms of $\%M$, $\%A$, $\%EA$, and the DAF composition of the DB fuel.

$$\begin{aligned}
N_{DB,DAF,in} &= 1 \\
N_{O_2,in} &= \left(\frac{\%EA}{100} + 1 \right) \left(\frac{DAF_C}{12.01} + \frac{DAF_H}{4.03} + \frac{DAF_S}{32.06} - \frac{DAF_O}{31.99} \right) \\
&\quad * (100 - \%M - \%A) \\
N_{N_2,in} &= \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) \left(\frac{DAF_C}{12.01} + \frac{DAF_H}{4.03} + \frac{DAF_S}{32.06} - \frac{DAF_O}{31.99} \right) \\
&\quad * (100 - \%M - \%A) \\
N_{CO_2,out} &= \frac{DAF_C}{12.01} (100 - \%M - \%A) \\
N_{H_2O_{(g)},out} &= \frac{DAF_H}{2.02} (100 - \%M - \%A) + \frac{\%M}{18.02} \\
N_{N_2,out} &= \left[\frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) \left(\frac{DAF_C}{12.01} + \frac{DAF_H}{4.03} + \frac{DAF_S}{32.06} - \frac{DAF_O}{31.99} \right) \right. \\
&\quad \left. + \frac{DAF_N}{28.01} \right] * (100 - \%M - \%A) \\
N_{SO_2,out} &= \frac{DAF_S}{32.06} (100 - \%M - \%A) \\
N_{O_2,out} &= \left[\frac{\%EA}{100} \left(\frac{DAF_C}{12.01} + \frac{DAF_H}{4.03} + \frac{DAF_S}{32.06} - \frac{DAF_O}{31.99} \right) \right] \\
&\quad * (100 - \%M - \%A)
\end{aligned} \tag{IV.14}$$

b) Conservation of Energy

The next step in evaluating the general combustion process in Fig. IV.1 is to use the first law of thermodynamics to compute adiabatic flame temperatures and thermal energy outputs. The steady state, conservation of energy for Fig. IV.1 can be written as:

$$0 = Q - W + N_{DB,DAF,in} \bar{h}_{DB,in} + \sum_{air,in} N_k \bar{h}_k - \sum_{products,out} N_k \bar{h}_k \tag{IV.15}$$

Since the combustion processes discussed in this paper occur at relatively low pressures and high temperatures, all gases can be assumed to be ideal. The enthalpies, \bar{h}_k , have

two components: the enthalpies of formation, $\bar{h}_{f,k}^0$, and the changes in thermal enthalpy, $\Delta\bar{h}_{t,k}^T$. The changes in thermal enthalpy are functions of only temperature due to the ideal gas assumption, and if one further assumes constant specific heats, $\bar{c}_{p,k}$, the changes in thermal enthalpy can be written as:

$$\Delta\bar{h}_{t,k}^T = \bar{c}_{p,k} \int_{298K}^T dT' = \bar{c}_{p,k} (T - 298) \quad (\text{IV.16})$$

The total enthalpy of a species is therefore:

$$\bar{h}_k = \bar{h}_{f,k}^0 + \bar{c}_{p,k} (T - 298) \quad (\text{IV.17})$$

The temperature, 298 K (537 R, 77 °F), is assumed to be the ambient temperature in which both fuel and air enter the CV in Fig. IV.1. In reality, specific heats are functions of temperature and cannot be removed from the temperature integral in equation (IV.16); however, since adiabatic flame temperatures are not expected to be too high due to the fact that DB is a low quality fuel, one can assume constant specific heats to a fairly good approximation.

Furthermore, the enthalpy of the DB fuel can be found with the following

$$\bar{h}_{DB,in} = HHV_{DB,DAF} MW_{DB,DAF} + N_{CO_2,out} \bar{h}_{f,CO_2}^0 + N_{H_2O(g),out} \bar{h}_{f,H_2O(l)}^0 + N_{SO_2,out} \bar{h}_{f,SO_2}^0 \quad (\text{IV.18})$$

This equation is derived in Appendix B. The molecular weight of the DAF DB, $MW_{DB,DAF}$, is simply:

$$MW_{DB,DAF} \left[\frac{\text{kg DB, DAF}}{100 \text{ kg as rec}} \right] = 100 - \%M - \%A \quad (\text{IV.19})$$

To calculate adiabatic flame temperatures, assume that the heat transfer, $Q = 0$, and the work, $W = 0$. Also, since the enthalpies of formation are zero for O_2 and N_2 , and since the integral in equation (IV.16) is zero when $T = 298 \text{ K}$, the terms $\sum_{air,in} N_k \bar{h}_k$ are also zero. Hence (IV.15) reduces to the following.

$$\sum_{products,out} N_k \bar{h}_k = N_{DB,DAF,in} \bar{h}_{DB,in} \quad (IV.20)$$

Expanding the summation for the products and inserting equations (IV.17) and (IV.18) one will obtain the following.

$$\begin{aligned} & N_{CO_2,out} \left\{ \bar{h}_{f,CO_2}^0 + \bar{c}_{p,CO_2} (T_{out} - 298) \right\} + N_{H_2O(g),out} \left\{ \bar{h}_{f,H_2O(g)}^0 + \bar{c}_{p,H_2O(g)} (T_{out} - 298) \right\} \\ & + N_{N_2,out} \left\{ \bar{c}_{p,N_2} (T_{out} - 298) \right\} + N_{SO_2,out} \left\{ \bar{h}_{f,SO_2}^0 + \bar{c}_{p,SO_2} (T_{out} - 298) \right\} \\ & + N_{O_2,out} \left\{ \bar{c}_{p,O_2} (T_{out} - 298) \right\} + m_{ash,out} \left\{ c_{p,ash} (T_{out} - 298) \right\} \\ & = N_{DB,DAF,in} \left(HHV_{DB,DAF} MW_{DB} + N_{CO_2,out} \bar{h}_{f,CO_2}^0 + N_{H_2O(g),out} \bar{h}_{f,H_2O(l)}^0 \right. \\ & \quad \left. + N_{SO_2,out} \bar{h}_{f,SO_2}^0 \right) \end{aligned} \quad (IV.21)$$

Here, T_{out} is the temperature of the gaseous combustion products leaving the CV, which is approximately equal to the adiabatic flame temperature. Solving for T_{out} one can obtain

$$T_{out} [K] = \frac{N_{DB,in} \bar{h}_{DB,in} - \sum_{products,out} N_k \bar{h}_{f,k}^0}{\sum_{products,out} N_k \bar{c}_{p,k}} + 298. \quad (IV.22)$$

Keep in mind that this equation is an approximation due to the assumption of constant specific heats. For larger temperature differences due to higher quality fuels, it may be preferred to use polynomial functions of temperature for the specific heats or ideal gas tables and numerically solve for the adiabatic flame temperature. However, for the

present work, equation (IV.22) will be adequate. Also, if the combustion air is preheated, then $\sum_{air,in} N_k \bar{h}_k$ does not equal zero, and hence the adiabatic flame temperature would be:

$$T_{out} [K] = \frac{N_{DB,in} \bar{h}_{DB,in} + (T_{in} - 298) \sum_{air,in} N_k \bar{c}_{p,k} - \sum_{products,out} N_k \bar{h}_{f,k}^0}{\sum_{products,out} N_k \bar{c}_{p,k}} + 298. \quad (IV.23)$$

In cases of evaluating heat outputs for steam generation and boiler efficiencies, one first has to return to equation (IV.15). The work, W , is still zero, as well as $\sum_{air,in} N_k \bar{h}_k = 0$. However, the heat transfer, Q , will be the dependant variable, and one has to solve the conservation of energy equation for it. Thus, (IV.15) reduces similarly to the following.

$$Q_w \left[\frac{kJ}{100 \text{ kg as rec DB}} \right] = \sum_{products,out} N_k \bar{h}_k - N_{DB,in} \bar{h}_{DB,in} \quad (IV.24)$$

In this equation, T_{out} , is the stack temperature, and Q_w is the amount of heat transferring to the boiler water for every 100 kg of DB fuel fired.

c) Cofiring Dairy Biomass with Additional Fuel

When the moisture content of the dairy biomass is too high, the combustible percentage is inadequate to vaporize all the moisture in the DB. One option may be to use an additional biomass fuel such as partially composted feedlot biomass with less moisture to increase the overall combustible percentage. First, define the extra amount

of fuel, EF , as the kilograms of additional fuel per kilogram of as received DB, and assume that 100 kg of the blend is fired.

$$EF = \frac{m_{EF}}{m_{DB}} \quad (IV.25)$$

$$m_{blend} = m_{DB} + m_{EF} = 100$$

Solving for m_{DB} and m_{EF} :

$$m_{DB} = \frac{100}{1 + EF} \quad (IV.26)$$

$$m_{EF} = 100 \left(\frac{EF}{1 + EF} \right)$$

One can set up this problem exactly like the solution for firing 100 kg of a single fuel by summing each element in the combustibles of each of the fuels. The amount of each combustible element in the fuel blend can be computed with the following.

$$C_{blend} = \frac{DAF_{C,DB} (100 - \%M_{DB} - \%A_{DB}) + EF * DAF_{C,EF} (100 - \%M_{EF} - \%A_{EF})}{12.01(1 + EF)}$$

$$H_{blend} = \frac{DAF_{H,DB} (100 - \%M_{DB} - \%A_{DB}) + EF * DAF_{H,EF} (100 - \%M_{EF} - \%A_{EF})}{1.008(1 + EF)}$$

$$N_{blend} = \frac{DAF_{N,DB} (100 - \%M_{DB} - \%A_{DB}) + EF * DAF_{N,EF} (100 - \%M_{EF} - \%A_{EF})}{14.0067(1 + EF)} \quad (IV.27)$$

$$O_{blend} = \frac{DAF_{O,DB} (100 - \%M_{DB} - \%A_{DB}) + EF * DAF_{O,EF} (100 - \%M_{EF} - \%A_{EF})}{15.997(1 + EF)}$$

$$S_{blend} = \frac{DAF_{S,DB} (100 - \%M_{DB} - \%A_{DB}) + EF * DAF_{S,EF} (100 - \%M_{EF} - \%A_{EF})}{32.064(1 + EF)}$$

Notice that here, like with DB fuel, the $DAF_{k,EF}$ values characterize the added fuel. The moisture and ash percentages of the extra fuel can also be variables in the analysis. The

moisture percentage of the blend which should be less than the moisture percentage of the DB alone can be computed with the following.

$$\%M_{blend} = \left(\frac{1}{1+EF} \right) \%M_{DB} + \left(\frac{EF}{1+EF} \right) \%M_{EF} \quad (IV.28)$$

Similarly the ash percentage is

$$\%A_{blend} = \left(\frac{1}{1+EF} \right) \%A_{DB} + \left(\frac{EF}{1+EF} \right) \%A_{EF}. \quad (IV.29)$$

Furthermore one can write the molecular weight of the blend as

$$MW_{blend} = 100 - \%M_{blend} - \%A_{blend}. \quad (IV.30)$$

The HHV of the blend can also be written as the following.

$$\begin{aligned} HHV_{as\ rec,blend} &= \left(\frac{1}{1+EF} \right) \frac{HHV_{DAF,DB} (100 - \%M_{DB} - \%A_{DB})}{100} \\ &\quad + \left(\frac{EF}{1+EF} \right) \frac{HHV_{DAF,EF} (100 - \%M_{EF} - \%A_{EF})}{100} \quad (IV.31) \\ HHV_{DAF,blend} &= \frac{HHV_{as\ rec,blend} * 100}{(100 - \%M_{blend} - \%A_{blend})} \end{aligned}$$

Modeling the blend in this way, one can use equations (IV.2) and (IV.15) to formulate similar solutions as the single fuel firing model discussed above.

Model II: Regenerative Combustion System for Flushed Dairy Manure

Model I used direct combustion; however when the combustible percentage is very low, the exhaust product temperature (flame temperature) is too low to allow steady combustion to occur in the burner. If the combustion air is preheated, then the flame temperature can be increased. First a regenerative combustor design that utilizes a

counter flow heat exchanger will be modeled. Secondly, a slightly different regenerative combustor design will be presented with a parallel flow heat exchanger.

a) Preheated-Air Combustor Design with Counter Flow Heat Exchanger

The regeneration system with the counter flow heat exchanger is shown in Fig.

IV.2.

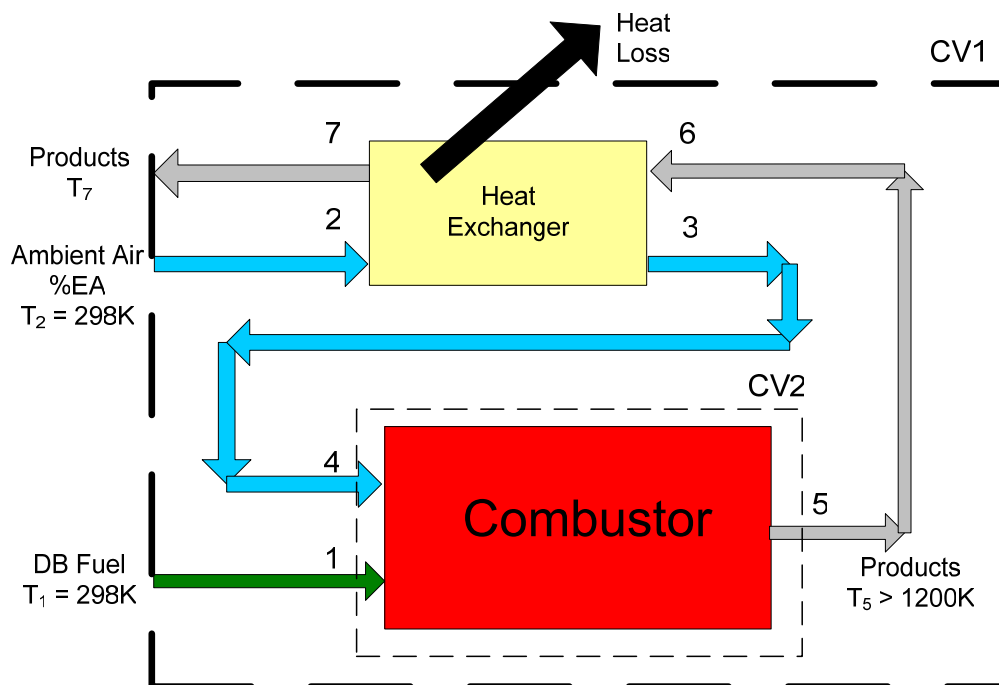


Fig. IV.2. Preheated-air combustor design with counter-flow heat exchanger.

The analysis of this arrangement may begin with the assumption that the flame temperature in the combustor must be at least 1200 K (1700°F). The minimum ignition temperatures for methane and charcoal are 810 K and 650 K , respectively, while carbon monoxide (CO) has a minimum ignition temperature of 1030 K (Bartok and Sarofim, 1991). Considering that DB is a lower quality fuel, a 1200 K flame temperature is

probably more suitable to ignite the DB. If it is, then one can assume that it is possible to generate a stable flame in the combustor and burn DB solids at a steady rate. However, if equation (IV.22) is used to calculate the flame temperature of the separated solids (80% moisture, 2% ash) fired with 10% excess ambient air in the simple case in Model I, then one finds that the flame temperature is only about 728 K ($851\text{ }^{\circ}\text{F}$). Thus, one must find a way of increasing the flame temperature.

Consider the preheated-air combustor design in Fig. IV.2. A heat exchanger is coupled with the combustor in order to preheat the combustion air with the hot products exiting at point 7 towards a boiler chamber or perhaps some other process. Cold excess air enters the system at state 2 and flows in the opposite direction of the products of combustion (state 6) that exited the combustor at state 5. The air will exit the heat exchanger at a higher temperature at state 3 and enter the combustor at state 4. Presumably this design can ease the combustible requirements (or moisture restrictions, depending on how one wants to view the problem) on the DB solids by increasing the flame temperature.

Here, T_7 and T_4 are governed by energy balances about the control volumes CV1 and CV2. When conducting the energy balances on these control volumes one should obtain equations similar to (IV.22) and (IV.23) discussed earlier. However, to add a degree of freedom to the problem, suppose that there is a heat loss in the heat exchanger causing T_7 to be lower than the ideal, adiabatic case. One can define the heat exchanger's efficiency as the ratio of the heat gained by the combustion air over the heat lost by the products.

$$\eta_{HX} = \frac{\sum_{air} N_k \bar{c}_{p,k} (T_3 - T_2)}{\sum_{products} N_k \bar{c}_{p,k} (T_6 - T_7)} \quad (IV.32)$$

If the heat does not transfer from the hot products to the incoming combustion air, then it is lost to the surrounding atmosphere, thus causing η_{HX} to be less than one (less than ideal and adiabatic). Solving (IV.32) for T_3 ($=T_4$) and noting that T_6 is equal to T_5 if there are no losses in the pipes:

$$T_4 = \frac{\eta_{HX} \sum_{products} N_k \bar{c}_{p,k} (T_5 - T_7)}{\sum_{air} N_k \bar{c}_{p,k}} + T_2 \quad (IV.33)$$

The energy balance of CV4 shows that:

$$N_{DB,DAF,1} \bar{h}_{DB,1} + \sum_{air} N_k \bar{c}_{p,k} (T_4 - 298) = \sum_{products} N_k (\bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_5 - 298)) \quad (IV.34)$$

Now, inserting (IV.33) into (IV.34) and solving for T_7 :

$$T_7 = \frac{1}{\eta_{HX}} \left[\frac{N_{DB,DAF,1} \bar{h}_{DB,1} + (T_2 - 298) \sum_{air} N_k \bar{c}_{p,k} - \sum_{products} N_k \bar{h}_{f,k}^0}{\sum_{products} N_k \bar{c}_{p,k}} - (1 - \eta_{HX}) T_5 + 298 \right] \quad (IV.35)$$

Furthermore, one additional constraint on this system is the second law, which places limits on how hot the combustion gases can be at T_4 , and how cool the exiting exhaust temperature can be at T_7 . More specifically,

$$\begin{aligned} T_7 &> T_2, \text{ and} \\ T_6 &> T_3. \end{aligned} \quad (IV.36)$$

Otherwise, heat transfer will not occur.

One can also define and compute the heat exchanger's effectiveness as an additional way to represent the second law.

$$\varepsilon = \frac{\sum_{air} N_k \bar{c}_{p,k} (T_3 - T_2)}{\sum_{air} N_k \bar{c}_{p,k} (T_6 - T_2)} = \frac{(T_3 - T_2)}{(T_6 - T_2)} \quad (IV.37)$$

The effectiveness can never be negative or greater than one. For each set of values for moisture and ash percentage, equation (IV.37) represents the required minimum heat exchanger effectiveness. The results of equations (IV.35), (IV.36), and (IV.37) in terms of %M, %A and %EA will be presented and discussed in the next chapter.

b) Preheated-Air Combustor Design with Parallel Flow Heat Exchanger

Now, consider a slight variation of the regenerative system that uses a parallel flow heat exchanger instead of a counter flow exchanger. This variation is sketched in Fig. IV.3.

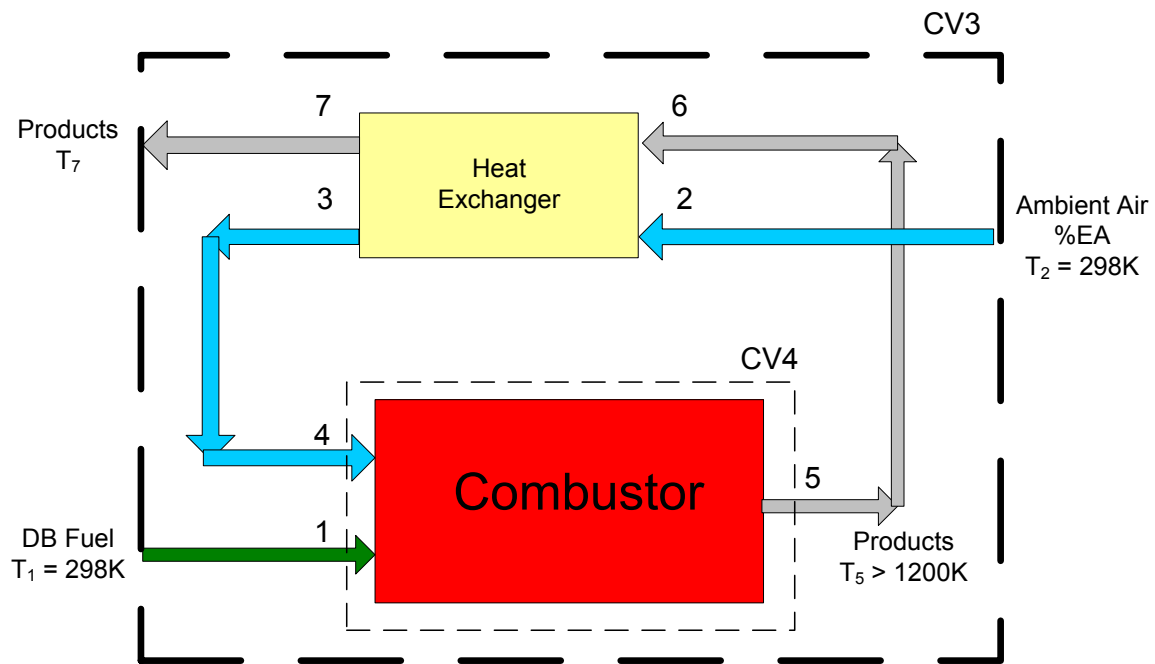


Fig. IV.3. Preheated-air combustor design with parallel flow heat exchanger.

Since the temperatures of the exhaust exiting the heat exchanger and of the combustion air entering the combustor are both governed by energy balances about CV3 and CV4 in the same way as the previous model, the analysis for Fig. IV.3 is identical to that of Fig. IV.2 if the same temperature is prescribed at T_5 . Since the analysis and results will be exactly the same, suppose instead that one considers an ideal case where the heat exchanger is ideal ($\eta_{HX} = 1$).

The unknowns are the temperatures at point 7 and point 4 (T_7 and T_4 respectively). To further simplify the analysis, assume that the contact surface area in the heat exchanger is large enough so that $T_7 \cong T_3$. Furthermore, if the heat loss in the pipe connecting point 3 to point 4 is small, then $T_3 \cong T_4$. Thus, one can assume

that $T_7 \cong T_4$. Therefore, the analysis for the preheated-air combustor design can be said to be the following.

$$T_4 = \frac{\sum_{products,5} N_k (\bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_5 - 298)) - N_{DB,1} \bar{h}_{DB,1}}{\sum_{air,4} N_k \bar{c}_{p,k}} + 298 \quad (IV.38)$$

and

$$T_7 = \frac{N_{DB,1} \bar{h}_{DB,1} - \sum_{products,7} N_k \bar{h}_{f,k}^0}{\sum_{products,7} N_k \bar{c}_{p,k}} + 298 \quad (IV.39)$$

From the adiabatic energy balances about CV3 and CV4. Since these two temperatures are approximately equal, then

$$\begin{aligned} & \frac{N_{DB,1} \bar{h}_{DB,1} - \sum_{products,7} N_k \bar{h}_{f,k}^0}{\sum_{products,7} N_k \bar{c}_{p,k}} \\ &= \frac{\sum_{products,5} N_k (\bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_5 - 298)) - N_{DB,1} \bar{h}_{DB,1}}{\sum_{air,4} N_k \bar{c}_{p,k}}. \end{aligned} \quad (IV.40)$$

The solutions to this equation are discussed in the next chapter. However, basically, if one knows how much ash is in the separated DB solids, %A, and assumes an amount of excess air, %EA, then one can solve for %M, which would be the optimum allowable amount of moisture in the DB fuel to burn at T_5 with this idealized preheated air design.

Model III: Vaporizing Moisture from Flushed Manure in a Fire-tube Boiler

As discussed in the literature review, flushed dairy manure can have moisture percentages up to 97%. If the moisture is this high, then no type of regenerative design could possibly independently fire the manure directly and still maintain a prescribed flame temperature. However, utilization of some of the separation and dewatering equipment, such as solid screen separators and auger presses discussed earlier, may be used to lower the moisture percentage in the manure solids that are fired in the combustor. Yet, even after the separation and/or dewatering processes, the remaining water still contains high concentrations of phosphorus and other nutrients that create the potential for pollution. If one is to design a sufficient disposal system, then this unclean water must also be eliminated.

Suppose that the exhaust products generated from the previous models are sent through a fire tube boiler as depicted in Fig. IV.4.

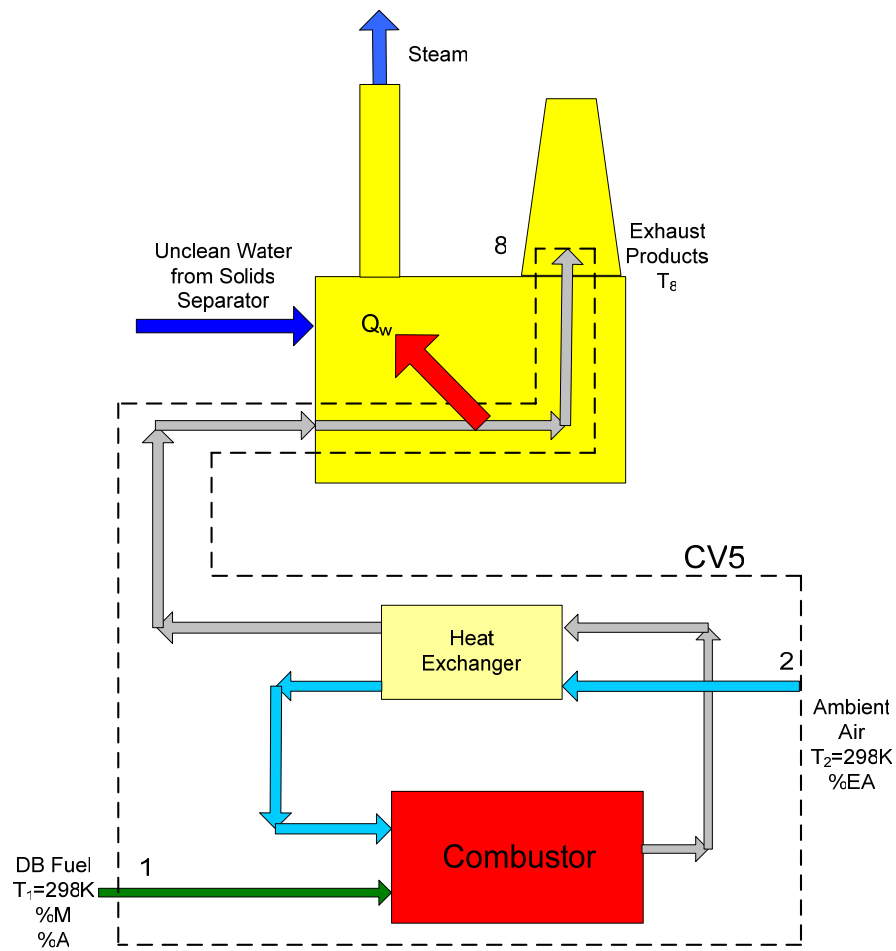


Fig. IV.4. Boiler analysis.

The unclean water can be fed or sprayed into the boiler chamber. As the unclean water is vaporized, much of the remaining solids should fall to the boiler chamber floor and be removed periodically, similar to blow-down in many conventional boilers. If this design is found to be viable, then the performance of this boiler system as a waste disposal system for flushed manure can be determined by gauging the amount or percentage of the unclean water that can be vaporized in the boiler chamber by burning the solids (i.e.

disposal efficiency, $\eta_{disposal}$). The first step is to form a control volume around the preheated-air combustor and the boiler chamber, as seen in Fig. IV.4.

DB fuel and air are fired in the combustor, producing hot combustion products that travel through the boiler chamber. In the boiler, hot gases flow through tubes which are sprayed with unclean water (separated water). The heat transferred from the products to the sprayed water is denoted as Q_w . The products leave the chamber through the exhaust stack at a lower temperature, T_8 . Notice that point 8 in Fig. IV.4 is just outside of the chamber and before any optional recuperators or condensing heat exchanger.

The analysis begins with equation (IV.24), which can be written as

$$\begin{aligned}
 Q_w = & N_{CO_2,8} \left(\bar{h}_{f,CO_2}^0 + \bar{c}_{p,CO_2} (T_8 - 298) \right) + N_{H_2O,8} \left(\bar{h}_{f,H_2O(g)}^0 + \bar{c}_{p,H_2O(g)} (T_8 - 298) \right) \\
 & + N_{N_2,8} \left(\bar{c}_{p,N_2} (T_8 - 298) \right) + N_{SO_2,8} \left(\bar{h}_{f,SO_2}^0 + \bar{c}_{p,SO_2} (T_8 - 298) \right) \\
 & + N_{O_2,8} \left(\bar{c}_{p,O_2} (T_8 - 298) \right) + m_{ash,8} c_{p,ash} (T_8 - 298) \\
 & - N_{DB,DAF,1} \bar{h}_{DB,1}
 \end{aligned} \tag{IV.41}$$

Using equations (IV.14) and (IV.18), one can express this equation in terms of %M, %A, %EA, and the stack temperature, T_8 . In the next chapter, results for Q_w will be presented in terms of each of these variables.

Typically, boiler performance is expressed as an efficiency, which for this case can be written as

$$\eta_{boiler} = \frac{|Q_w|}{HHV_{DB,DAF} * (100 - \%M - \%A)} * 100. \tag{IV.42}$$

Notice that the heat exchanger in Fig. IV.4 does not contribute to the boiler efficiency. The purpose of the heat exchanger is merely to increase the actual flame temperature in the combustor. The water sprayed into the boiler chamber evaporates to become steam. This water may be pumped up to a prescribed boiler pressure to produce high pressure steam. See Fig. IV.5.

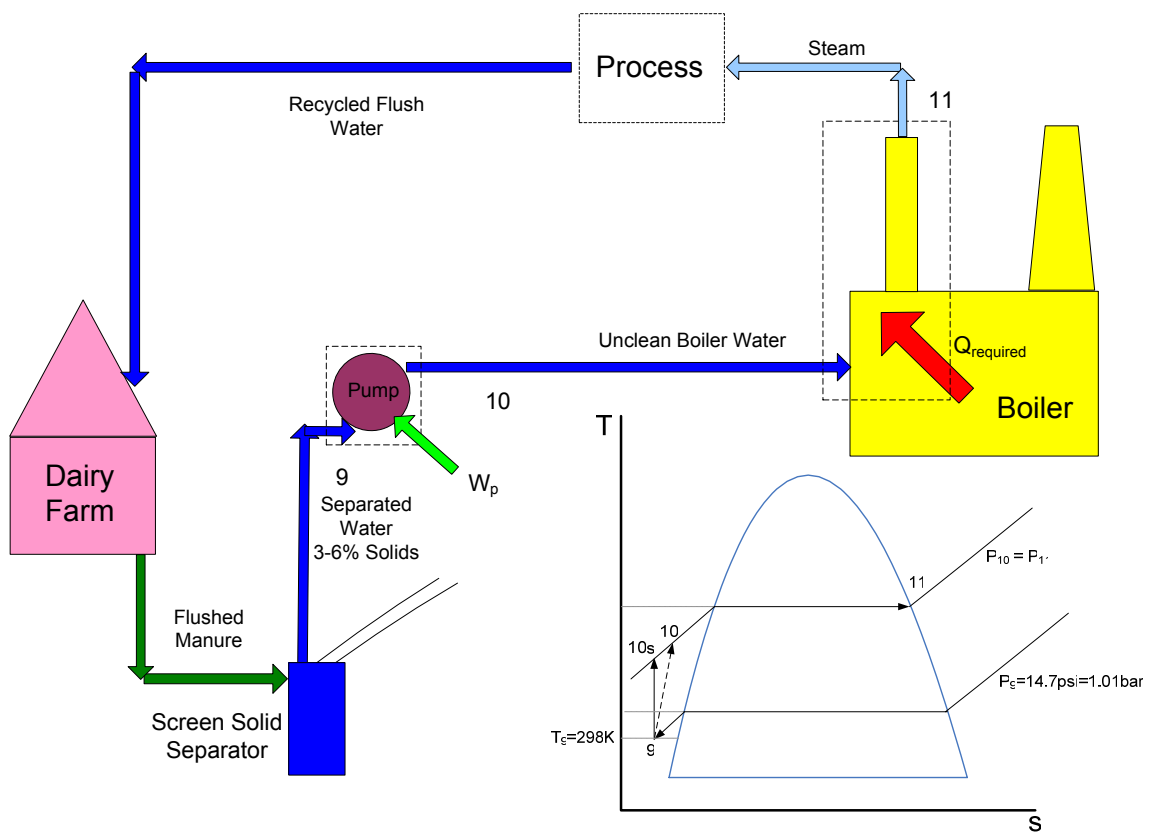


Fig. IV.5. Separated water processes and T-s diagram.

A first law analysis of the water in the boiler shows that:

$$Q_{required} = m_w (h_{11} - h_{10}) \quad (IV.43)$$

Where m_w is the mass of the water per 100 kg of DB fuel fired in the combustor. Recall that Q_w is the heat released per 100 kg of DB. However, $Q_{required}$ in equation (IV.43) may not be the same as Q_w in equation (IV.41). Therefore, one must compute m_w and find the required heat to vaporize all the water, $Q_{required}$. Consider Fig. IV.6, where it is assumed that the flushed manure coming from the dairy is separated into DB solids and water.

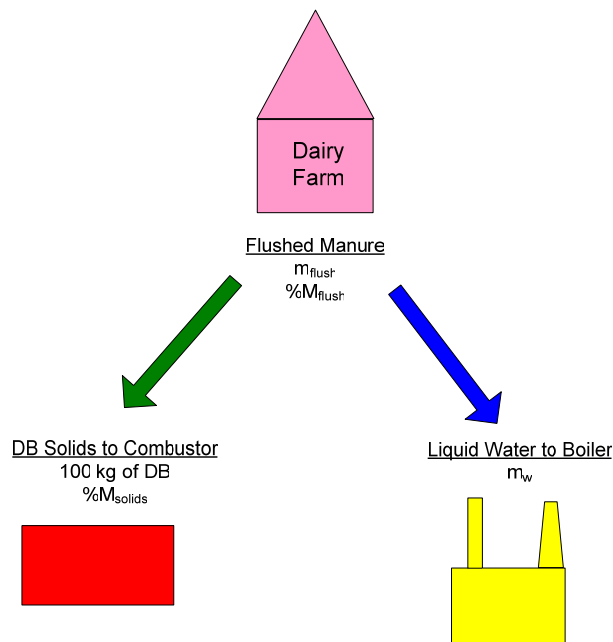


Fig. IV.6. Overall mass flow for disposal system.

Since it is presumed that all the solids in the flush will eventually be fired in the combustor, Fig. IV.6 is a good approximation of the overall flow of mass in the system. It can be shown that the mass of the water in terms of the moisture percentage in the flush, $\%M_{flush}$ and the moisture percentage in the DB solids $\%M_{solids}$ can be written as:

$$m_w \left[\frac{\text{kg}}{100 \text{ kg of DB solids fired}} \right] = \frac{(\%M_{\text{flush}} - \%M_{\text{solids}})}{\left(1 - \frac{\%M_{\text{flush}}}{100}\right)} \quad (\text{IV.44})$$

Finally one can define the disposal efficiency of the system.

$$\eta_{\text{disposal}} = \frac{Q_w}{Q_{\text{required}}} * 100 = \frac{Q_w}{m_w (h_{11} - h_{10})} * 100 \quad (\text{IV.45})$$

Typically, since $m_w \gg 100\text{kg}$ of DB solids, the disposal efficiency is low. However, as discussed above, extra fuel can be blended with the DB solids to produce more heat. The next chapter contains parametric studies of this system's disposal efficiency, as well as an investigation to how well various fuel blends may improve this efficiency.

Overall Model of Flushed Manure Disposal System

One can combine the above models into one overall system or scheme for disposing flushed dairy manure. A representation of the proposed waste disposal system for flushed dairy manure is shown in Fig. IV.7. The manure is flushed from the dairy with about 7% solids (approximately 3% ash as received). The stream of flushed manure enters a screen solid separator which removes a portion of the solids. The separated solids still have moisture contents of 80%, but only about 2% ash contents. (Note that these numbers are taken from the results of a fuel analysis discussed in the next chapter). After some preconditioning, the separated solids are fired in a combustor or furnace. The remaining liquid manure is essentially unclean water, and may still have up to 6% solids depending on the separator efficiency. The unclean water is sent to a boiler chamber and sprayed over tubes containing hot combustion products.

The heat generated from firing the solids can be used to vaporize the unclean water in a fire-tube boiler. Most of the solids in the sprayed water fall by gravity to the bottom of the boiler chamber and are collected periodically. These collected solids (which may be mostly inert material if the separator does not remove the ash as efficiently) can be sent back to the combustor as additional fuel. The steam generated from the boiler maybe impure if the unclean water is not treated before entering the chamber.

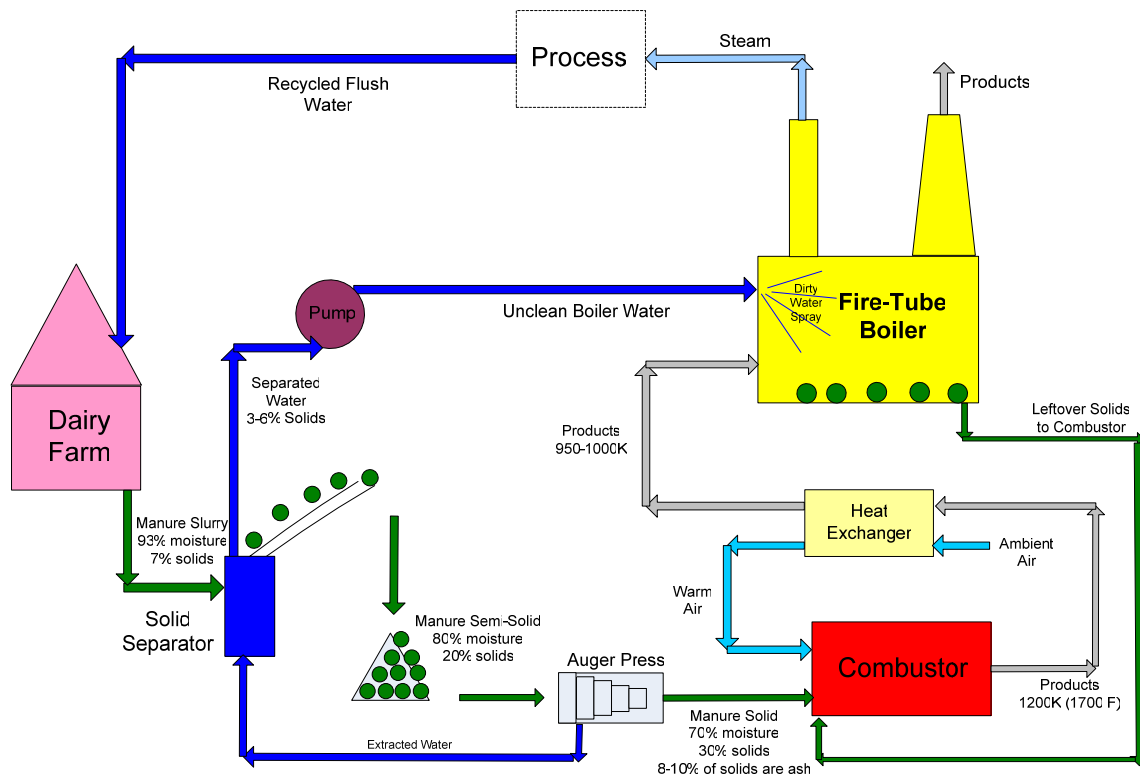


Fig. IV.7. Diagram of proposed waste management plan for flushed dairy manure.

On top of being impure, the steam may also be, at best, saturated steam. This limits the processes that can be performed with the steam. However, it may be possible to meet

some thermal loads in the milking center of the dairy with the steam produced from this disposal plan. A future study should be conducted to investigate how pure this steam will be. Also, since the combustion products will also have a large amount of steam, a condensing heat exchanger at the exhaust stack maybe an option to recover some additional flushing water.

Yet, the primary benefit of this system is that the flushed DB is reduced to combustion products, ash in the combustor, and relatively pure recycled water for further flushing, thus eliminating the need for storage lagoons and land application.

Model IV: Proposed Waste Disposal System for Vacuumed Dairy Manure

A more direct way of collecting the DB solids is to use vacuum machines instead of a flush system. The DB collected from vacuums is generally about 50% moisture and 50% solids (Matthews, et al., 2003). However, there may be more ash in the solids of vacuumed manure than flushed manure, because the vacuum also picks up dust and dirt on the ground in the dairy free stalls. Yet, thermodynamically, this may be better because ash is not as much of a heat sink as moisture.

The waste disposal system for vacuumed dairy manure is similar to the previous system, as seen in Fig. IV.8. Yet, unlike the disposal system for flushed manure, the system for vacuumed manure does not have a requirement on vaporizing unclean water from a separator. Hence, boiler water can be put through a vapor power cycle to produce electricity from a steam turbine with relatively little pretreatment or purification. Furthermore, since pure steam is being produced, there are fewer restrictions on other possible thermal or heating processes.

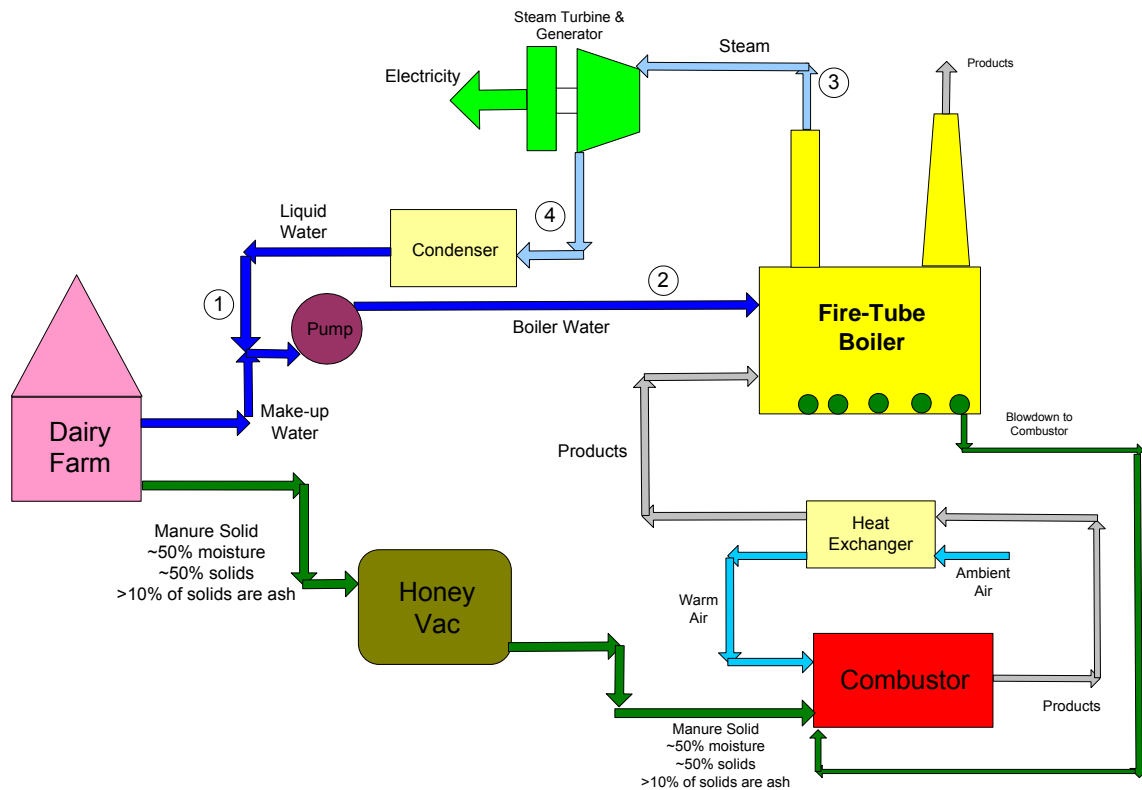


Fig. IV.8. Proposed waste disposal system for vacuumed dairy manure.

The present discussion for this disposal system will focus on the vapor power cycle since the analysis for firing the DB solids remains the same, except ash contents will likely be higher while moisture contents are lower than flushed manure.

Plug flow anaerobic digester systems, such as the one discussed in chapter 2, produce about 100 kW of electricity from 700 cows. One can consider this system successful if it can produce a competitive amount of power without using storage lagoons or effluent as fertilizer.

The vapor power cycle's thermal efficiency can be written as

$$\eta_{thermal} = \frac{\dot{W}_{cycle}}{\dot{Q}_w} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_w} \quad (IV.46)$$

Similar to equation (IV.42), one can express \dot{Q}_w in terms of %M, %A, and the mass firing rate, \dot{m}_f .

$$\dot{Q}_w = \eta_{boiler} \dot{m}_f HHV_{DB,DAF} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right) \quad (IV.47)$$

Plugging (IV.47) into (IV.46):

$$\eta_{thermal} = \frac{\dot{W}_{cycle}}{\eta_{boiler} \dot{m}_f HHV_{DB,DAF} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right)} \quad (IV.48)$$

Next, solving for the firing rate and defining the plant efficiency, η_{plant} , as the product of the thermal efficiency and the boiler efficiency, one can obtain the following expression for the vacuumed DB firing rate required to sustain a plant with a power capacity of \dot{W}_{cycle} .

$$\dot{m}_f = \frac{\dot{W}_{cycle}}{\eta_{plant} HHV_{DB,DAF} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right)}$$

with (IV.49)

$$\eta_{plant} = \eta_{boiler} \eta_{thermal}$$

In the next chapter, the firing rate will be plotted vs. %M and %A for different plant efficiencies. Also, one can make a more detailed model of the vapor power cycle; however, it is not essential to determining the performance of the proposed system for vacuumed DB. A classic algorithm for determining the vapor power cycle efficiency is given in Appendix C for reference or for future detailed work.

Model V: Proposed Combined Digestion and Firing System

A proposed combined digestion and firing system is depicted in Fig. IV.9. As discussed in the literature review, flushed manure from the dairy free stalls can contain up to 10% solids and be converted into biogas and effluent in a plug flow digester. From the digester, biogas is fired in a combustor, while effluent (remaining digested liquid manure) is sent to a settling basin or perhaps a water treatment center. From the combustor, products are sent to a fire-tube boiler, while leftover solids are sent to a combustor. The fire-tube boiler produces steam, which is used in a process, and dirty water spray, which is sent to a settling basin or water treatment center. The settling basin or water treatment center produces effluent, which is sent to a plug flow digester, and recycled flush water, which is sent to a dairy farm. The plug flow digester produces flushed DB (3-10% solids, 90-97% moisture), which is sent to a settling basin or water treatment center, and biogas, which is sent to a combustor. The combustor produces products, which are sent to a fire-tube boiler, and ambient air, which is sent to a combustor. The fire-tube boiler produces products, which are sent to a combustor, and leftover solids to combustor, which are sent to a combustor.

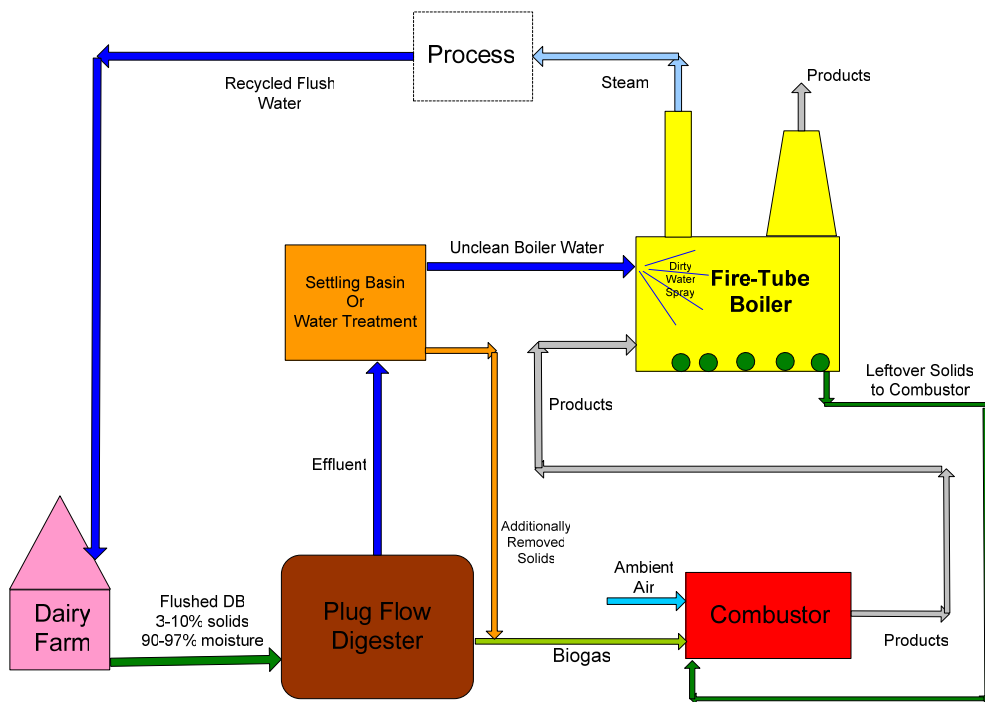


Fig IV.9. Proposed combined digestion and firing system.

From the water treatment center, relatively clean or unclean boiler water (depending on the type and quality of the effluent treatment) is fed or sprayed into the fire-tube boiler and vaporized into steam. Hot products from the combustor are once again sent through the boiler chamber in tubes. Any leftover solids can be periodically

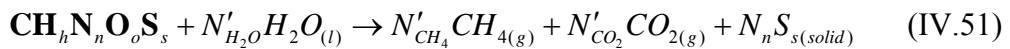
cycled back to the combustor as additional fuel or handled and processed in some other way.

The analysis for this system, as one may expect, is very similar to the direct firing system for flushed manure discussed above. However, modeling the actual production of biogas from the as received dairy biomass is original to this problem and will be discussed presently.

The elements in the DB combustibles are the same as in equation (IV.1). At times it may be easier to normalize the empirical equation on a “per kmole of combustibles” basis, rather than a “per 100 kg of as received fuel” basis. For this case, since it is assumed that only the combustible material plays a roll in generating the biogas that will eventually be fired in the combustor, a normalized empirical formula will be used for the present model. Writing the normalized chemical formula as:

$$\begin{aligned}
 & \mathbf{CH}_h\mathbf{N}_n\mathbf{O}_o\mathbf{S}_s \\
 & \text{where} \\
 & h \left[\frac{\text{kmole of H}}{\text{kmole of DB, DAF}} \right] = \frac{H}{C}, \quad n = \frac{N}{C}, \quad o = \frac{O}{C}, \text{ and } s = \frac{S}{C} \quad (\text{IV.50}) \\
 & MW_{DB,DAF} \left[\frac{\text{kg DB, DAF}}{\text{kmole DB, DAF}} \right] = 12.01 + 1.008h + 14.0067n \\
 & \qquad \qquad \qquad + 15.997o + 32.064s
 \end{aligned}$$

Ideally, the following chemical reaction equation can be used to model the production of biogas.



The unknowns are N'_{H_2O} , N'_{CH_4} , and N'_{CO_2} . Here, the liquid water in the reactants is the portion of the water in the DB fuel that will combine with the combustibles to produce

methane (CH_4). Therefore, the effluent will consist of the original moisture minus the moisture used in the reaction, plus ash and the remaining solids, which in this case, are assumed to be composed of the remaining nitrogen and sulfur in the fuel, $N_n S_{s(\text{solid})}$.

$$\text{Effluent} \Rightarrow (w - N'_{\text{H}_2\text{O}}) + \text{Ash} + N_n S_{s(\text{solid})} \quad (\text{IV.52})$$

In reality, the biogas is composed of more than just CH_4 and CO_2 . Other trace elements such as H_2S are also present. Furthermore, not all the combustibles in the DB fuel are converted into biogas. However, thermodynamically, the analysis from equation (IV.51) may be a fairly good approximation as far as computing the thermal energy outputs for fired biogas produced from DB.

Solving the unknowns in equation (IV.51) in terms of the combustible elements:

$$N'_{\text{CH}_4} \left[\frac{\text{kmole of } \text{CH}_4}{\text{kmole of DB, DAF}} \right] = \frac{1}{2} + \frac{h}{8} - \frac{o}{4} \quad (\text{IV.53})$$

$$N'_{\text{CO}_2} = \frac{1}{2} - \frac{h}{8} + \frac{o}{4} \quad (\text{IV.54})$$

$$N'_{\text{H}_2\text{O}} = 1 - \frac{h}{4} - \frac{o}{2} \quad (\text{IV.55})$$

Since the assumption for this model is that the biogas is made of only CH_4 and CO_2 , the kmole fraction of methane in the gas is:

$$X_{\text{CH}_4} \left[\frac{\text{kmole of } \text{CH}_4}{\text{kmole of biogas}} \right] = \frac{N'_{\text{CH}_4}}{N'_{\text{CH}_4} + N'_{\text{CO}_2}} = \frac{1}{2} + \frac{h}{8} - \frac{o}{4} \quad (\text{IV.56})$$

Furthermore, the molecular weight of the biogas can be computed with the following:

$$MW_{\text{biogas}} \left[\frac{\text{kg of biogas}}{\text{kmole of DB, DAF}} \right] = 16N'_{\text{CH}_4} + 44N'_{\text{CO}_2} \quad (\text{IV.57})$$

Where 16 and 44 are the molecular weights of CH₄ and CO₂, respectively.

Also, the higher heating value of the biogas can be shown to be:

$$HHV_{biogas} \left[\frac{kJ}{kmole \text{ of biogas}} \right] = X_{CH_4} \left(\bar{h}_{f,CH_4}^0 - \bar{h}_{f,CO_2}^0 - 2\bar{h}_{f,H_2O(l)}^0 \right) \quad (IV.58)$$

Since the quantities of gases are usually measured by volume instead of mass, computing the volume of biogas produced per kmole of combustibles may be more useful. Assuming that the biogas is an ideal gas at standard temperature and pressure (298 K, 100 kPa), the standard volume is:

$$\bar{V} \left[\frac{m^3 \text{ of biogas}}{kmole \text{ of DB, DAF}} \right] = (N'_{CH_4} + N'_{CO_2}) \frac{\bar{R}T}{P} \quad (IV.59)$$

Where \bar{R} is the ideal gas constant, 8.314 kPa m³/kmol/K. On an as received basis of DB entering the digester, the mass and volume of the biogas are:

$$m_{biogas} \left[\frac{kg \text{ of biogas}}{kg \text{ of DB as rec}} \right] = \frac{MW_{biogas}}{MW_{DB,DAF}} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right) \quad (IV.60)$$

and

$$\bar{V}_{biogas} \left[\frac{m^3 \text{ of biogas}}{kg \text{ of DB as rec}} \right] = \frac{\bar{V}}{MW_{DB,DAF}} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right). \quad (IV.61)$$

Now, to model the combustor and the boiler in Fig. IV.9, consider CV6 in Fig. IV.10.

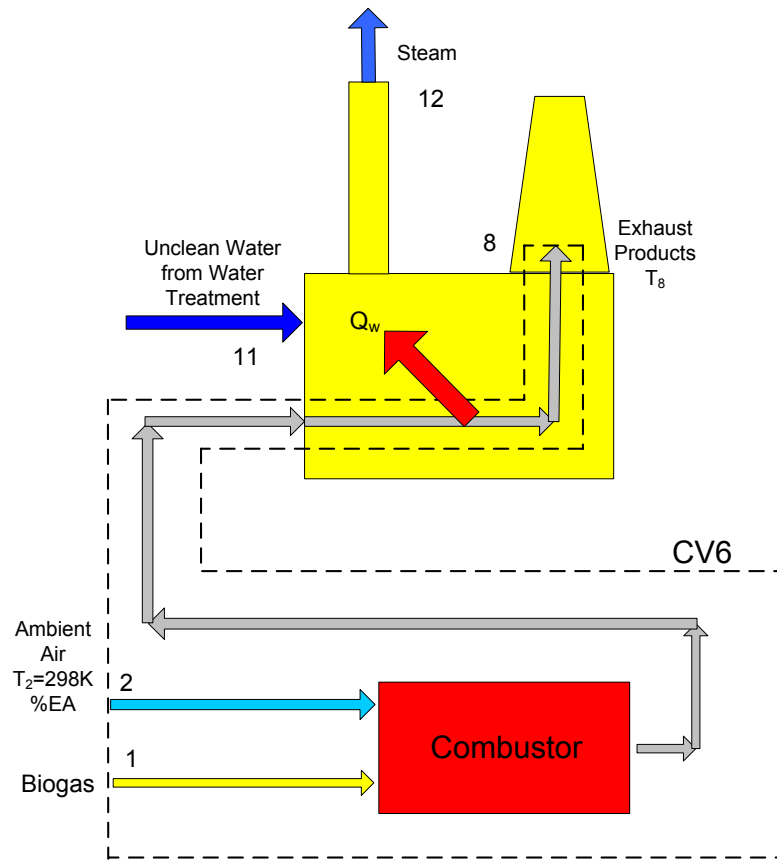
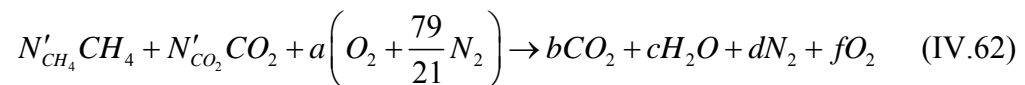


Fig. IV.10. Boiler system for biogas firing.

The following chemical reaction equation models the combustion of the biogas:



Just as was done for equations (IV.2) and (IV.51), the unknowns can be solved in terms of the fuel's composition. In this case, N'_{CH_4} and N'_{CO_2} . The solutions for the number of kmoles going in and out of CV6 are the following:

$$\begin{aligned}
N_{biogas} &= N'_{CH_4} + N'_{CO_2} \\
N_{O_2,in} &= 2N'_{CH_4} \left(\frac{\%EA}{100} + 1 \right), \\
N_{N_2,in} &= \frac{79}{21} \left[2N'_{CH_4} \left(\frac{\%EA}{100} + 1 \right) \right], \\
N_{CO_2,out} &= N'_{CH_4} + N'_{CO_2}, \\
N_{H_2O(g),out} &= 2N'_{CH_4}, \\
N_{N_2,out} &= \frac{79}{21} \left[2N'_{CH_4} \left(\frac{\%EA}{100} + 1 \right) \right], \\
N_{O_2,out} &= 2N'_{CH_4} \frac{\%EA}{100}.
\end{aligned} \tag{IV.63}$$

The flame temperature can be found (through an energy balance of just the combustor) to be the following (assuming that the temperature of the combustion air is at the ambient 298 K):

$$T_{flame,biogas} [K] = \frac{\sum_{biogas} N'_k \{ \bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_1 - 298) \} - \sum_{products} N_k \bar{h}_{f,k}^0}{\sum_{products} N_k \bar{c}_{p,k}} + 298 \tag{IV.64}$$

And the heat transfer to the boiler water can be found with an energy balance about CV6 to be:

$$\begin{aligned}
Q_w \left[\frac{kJ}{kmole DB, DAF} \right] &= \sum_{products} N_k \{ \bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_8 - 298) \} \\
&\quad - \sum_{biogas} N'_k \{ \bar{h}_{f,k}^0 + \bar{c}_{p,k} (T_1 - 298) \}
\end{aligned} \tag{IV.65}$$

Since the DB entering the plug flow digester may be preheated to lower hydraulic retention time (see literature review), T_1 may be higher than 298 K. The amount of liquid water that needs to be vaporized in the boiler can be found to be the following:

$$m_w \left[\frac{\text{kg of boiler water}}{\text{kg of DB as rec}} \right] = \frac{\%M}{100} - \left(\frac{18.02N'_{H_2O}}{MW_{DB,DAF}} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right) \right) \quad (\text{IV.66})$$

Finally, just as in Model III, a disposal efficiency can be defined as the heat released by the biogas combustion and the heat required to vaporize the boiler water.

$$\eta_{disposal} = \frac{\frac{|Q_w|}{MW_{DB,DAF}} \left(1 - \frac{\%M}{100} - \frac{\%A}{100} \right)}{m_w (h_{11} - h_{10})} \quad (\text{IV.67})$$

The results of this analysis will be presented in the next chapter. Furthermore, the performances of Model III and this model will be compared.

CHAPTER V

DATA INPUT AND DISCUSSION

In the first section of this chapter, a fuel analysis of samples of dairy biomass (DB) collected at the Broumley Dairy will be discussed. Next, parametric studies, results and discussions will be presented for the models derived in chapter IV.

Dairy Biomass Fuel Analysis

In order to model dairy biomass as a fuel, one needs property data that includes the combustible composition, ash percentage and moisture percentage. Samples of DB, collected at the Broumley Dairy were sent to Hazen Research Inc. in Golden, Colorado for analysis. The analyzed samples include the following:

- 1) Separated solids from the screen separator,
- 2) Partially composted solids from windrows of manure to be used as bedding,
- 3) Fully composted solids,
- 4) Flushed DB straight from the free stall (before the separator), and
- 5) Storage lagoon manure.

Ultimate, proximate, and heat value analysis were performed on the first four samples. Since the storage lagoon was not a primary part of the digester system process and will not play any role in any of the proposed combustion systems in this paper, only a moisture and ash percentage analysis was conducted on the fifth sample from the lagoon. In future work, samples of vacuumed DB may also be sent for analysis. Since the vacuum machine at the Broumley Dairy was not used to vacuum manure from the free stalls, no samples of vacuumed manure were taken. Furthermore, analysis of the

resulting unclean water from the separator may also be conducted in the future, however, since samples of the flush and separated solids were analyzed, the composition of the unclean water can be extrapolated in terms of the separator efficiency. The results of the fuel analysis are shown in Table V.1.

Table V.1. Ultimate, proximate and heat value analysis (as received basis) of DB samples.

As Received					
Parameter (by mass)	Separated Solid	PC-3-4 weeks Windrow	Fully Comp. 3-4 months	Flushed DB	Lagoon DB
Moisture	80.94	76.01	57.40	93.31	93.23
Ash	2.14	3.26	13.12	3.43	1.83
FC	3.64	4.83	7.04	0.45	--
VM	13.28	15.90	22.44	2.81	--
C	9.39	11.44	16.25	1.85	--
H	0.98	1.09	1.46	0.17	--
N	0.36	0.51	0.92	0.16	--
O	6.14	7.64	10.70	1.04	--
S	0.05	0.05	0.15	0.04	--
HHV (kJ/kg)	3468	4266	5965	668	--

Notice that the moisture content of the separated solids is still almost 81%. During composting the moisture percentage drops and the ash percentage increases as the manure dries, as can be seen in the 2nd and 3rd columns of Table V.1 for partially composted (PC) and fully composted manure. The proximate analysis yields the amount of fixed carbon (%FC) and volatile matter (%VM) that make up the combustible material in the fuel.

$$\%M + \%A + \%Cb = 100 \quad (\text{V.1})$$

$$\%Cb = \%VM + \%FC$$

$$\%M + \%A + \%VM + \%FC = 100 \quad (\text{V.2})$$

Here, %Cb is the combustible percentage. It is sometimes difficult to see how the combustibles and ash change during composting on an as received basis. However, one can convert these numbers to a dry basis as shown in Table V.2. The conversions are made with the following equation.

$$(Dry) = \frac{(As\ Rec.)}{(100 - \%M)} * 100 \quad (V.3)$$

Table V.2. Ultimate, proximate and heat value analysis (dry basis) of DB samples.

Dry Basis					
Parameter (by mass)	Separated Solid	PC-3-4 weeks Windrow	Fully Comp. 3-4 months	Flushed DB	Lagoon DB
Moisture	0.00	0.00	0.00	0.00	0.00
Ash	11.23	13.59	30.80	51.27	27.03
FC	19.10	20.13	16.53	6.73	--
VM	69.67	66.28	52.68	42.00	--
C	49.27	47.69	38.15	27.65	--
H	5.14	4.54	3.43	2.54	--
N	1.89	2.13	2.16	2.39	--
O	32.21	31.85	25.12	15.55	--
S	0.26	0.21	0.35	0.60	--
HHV (kJ/kg)	18193	17782	14002	9992	--

One can see that on a dry basis, during the composting, ash increases while the amount of VM decreases. This is confirmed in (Sweeten, Annamalai, et al., 2003) for feedlot biomass (FB). Yet, for the current study, perhaps the most interesting result from Table V.2 is the ash content in the flushed DB (51.27) vs. the ash content in the separated solids (11.23, which seems low). Since the combustibles contain relatively large particles of complex carbohydrates, the solid separator used at the Broumley Dairy may be more efficient at removing combustible solids than ash. It is also surprising that

over half of the solids in the flushed manure are inert despite using composted manure for bedding.

One can also focus on the combustibles in the fuel by removing the ash. When both ash and moisture are removed from the analysis, it is said to be on a dry, ash free (DAF) basis. The following equation converts from an as received basis to a DAF basis.

$$(DAF) = \frac{(As\ Rec.)}{(100 - \%M - \%A)} * 100 \quad (V.4)$$

Table V.3 shows the same DB fuel analysis on a DAF basis.

Table V.3. Ultimate, proximate and heat value analysis (DAF basis) of DB samples.

Dry, Ash Free Basis					
Parameter (by mass)	Separated Solid	PC-3-4 weeks Windrow	Fully Comp. 3-4 months	Flushed DB	Lagoon DB
Moisture	0.00	0.00	0.00	0.00	0.00
Ash	0.00	0.00	0.00	0.00	0.00
FC	21.51	23.30	23.88	13.80	--
VM	78.49	76.70	76.12	86.20	--
C	55.50	55.19	55.12	56.75	--
H	5.79	5.26	4.95	5.21	--
N	2.13	2.46	3.12	4.91	--
O	36.29	36.85	36.30	31.90	--
S	0.30	0.24	0.51	1.23	--
HHV (kJ/kg)	20494	20579	20234	20505	--

As expected, DB combustibles show much of the same characteristics as FB combustibles in (Sweeten, Annamalai, et al., 2003). The amount of volatile matter on a DAF basis decreases slightly during composting. Also the higher heating value (HHV) on a DAF basis is approximately 20,000 kJ/kg, just like the HHV of FB. Furthermore, the combustible content in each of the samples is virtually the same on a DAF basis.

The flushed DB sample is slightly different than the first three samples, particularly with the N and S contents. This may also be due to the solid separator. Yet the variations between the separated solids and the composted samples come from the slight changes in the volatile matter; however, these changes create minute variations when making combustion calculations.

Also, the combustible content is very similar for each FB sample. The following analysis on high-ash feedlot biomass (HA-FB) and low-ash feedlot biomass (LA-FB) was also conducted by Hazen Research Inc. The samples were collected by the Texas A&M Extension in Amarillo. See Table V.4.

Table V.4. Ultimate, proximate and heat value analysis (DAF basis) of FB samples.

DAF Basis		
Parameter (by mass)	HA-FB-Raw	LA-FB-Raw
Moisture	0.00	0.00
Ash	0.00	0.00
FC	18.19	19.11
VM	81.84	80.89
C	52.55	53.98
H	6.35	6.55
N	4.71	3.90
O	35.36	34.73
S	1.03	0.83
HHV (kJ/kg)	19049	21070

Here, the amounts of C, H, and O seem to be very similar to those of DB. However, the overall volatile matter for FB seems to be slightly more than that of DB, and conversely, fixed carbon is slightly less in FB. Also, FB seems to have greater amounts of N and S on a DAF basis.

An ash analysis was also conducted by Hazen Research on the separated DB solids. See Table V.5. The phosphorus and the potassium are found in this analysis and seem to be slightly higher for separated solids than high ash feedlot biomass and lower than those found in low ash feedlot biomass. Moreover, silicon and calcium make up a large percentage of the ash content. If the ash content in the unclean separated water is similar to this analysis, then perhaps the impurities in the generated steam in Models III and V could be predicted. However, this is left as future work.

Table V.5. Ash analysis of separated DB solids and high ash and low ash feedlot biomass.

Ash Analysis			
kg/kg Ash (%)	Separated Solid	HA-FB Raw	LA-FB Raw
Silicon, SiO₂	35.13	64.68	25.55
Aluminum, Al₂O₃	6.02	7.72	1.94
Titanium, TiO₂	0.21	0.44	0.27
Iron, Fe₂O₃	2.67	2.90	1.37
Calcium, CaO	17.60	7.09	20.20
Magnesium, MgO	6.12	2.34	7.17
Sodium, Na₂O	1.96	1.38	4.94
Potassium, K₂O	6.85	4.50	12.70
Phosphorus, P₂O₅	7.21	2.81	11.11
Sulfur, SO₃	2.55	1.06	4.46
Chlorine, Cl	0.32	0.68	5.02
Carbon dioxide, CO₂	2.15	1.35	1.71
Total ash analysis	88.79	96.95	96.44

Using these fuel analysis results, investigations and discussion of the five models discussed in the previous chapter can be carried out in terms of actual numbers.

Results for Model I and Discussion of Combustible Requirements

Before obtaining results for the different models and schemes, one should consider a simple thermodynamic test that can determine the viability of these schemes

without knowing the specifics of the processes involved with the disposal system. This test is essentially the same as Model I, except that the products will exit at some relatively low temperature near the boiling point of water (373 K) as seen in the control volume problem in Fig. V.1.

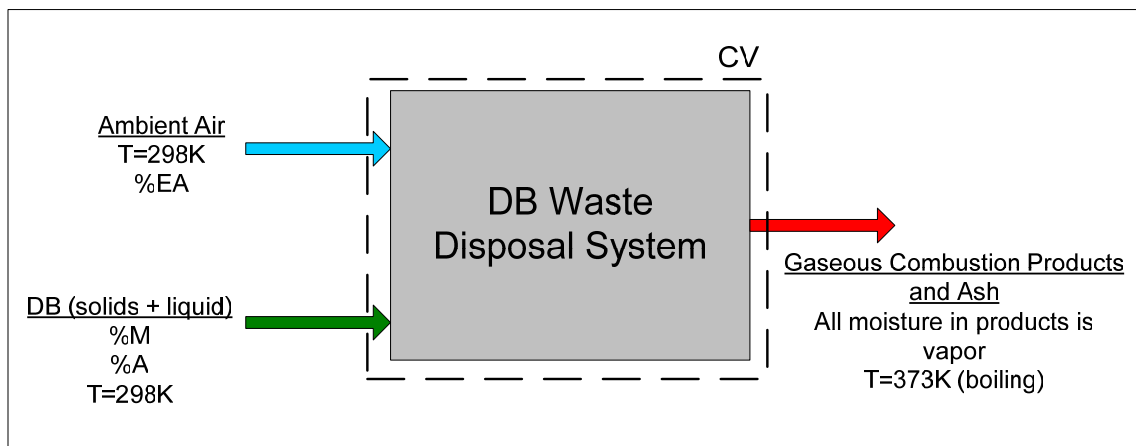


Fig. V.1. General schematic of proposed DB waste disposal systems.

This schematic represents the best possible case for a DB waste disposal system. All the moisture in the DB is vaporized and exits at the boiling temperature. This problem can be solved for different values of %A and %M in the same way as the general combustion problem in Model I. Beginning with equation (IV.14), assume that the DAF values of the separated solids in Table V.3 characterize the DB fuel in a combustion process. Plugging these numbers into equation (IV.14) one obtains the following.

$$\begin{aligned}
N_{DB,in} &= 1 \\
N_{O_2,in} &= 0.0493 * \left(\frac{\%EA}{100} + 1 \right) (100 - \%M - \%A) \\
N_{N_2,in} &= 0.0493 * \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) (100 - \%M - \%A) \\
N_{CO_2,out} &= 0.0462 * (100 - \%M - \%A) \\
N_{H_2O_{(g)},out} &= 0.0287 * (100 - \%M - \%A) + \frac{\%M}{18.02} \\
N_{N_2,out} &= \left[0.0493 * \frac{79}{21} \left(\frac{\%EA}{100} + 1 \right) + 0.0008 \right] (100 - \%M - \%A) \\
N_{SO_2,out} &= 0.0001 * (100 - \%M - \%A) \\
N_{O_2,out} &= \left[0.0493 * \left(\frac{\%EA}{100} \right) \right] (100 - \%M - \%A)
\end{aligned} \tag{V.5}$$

In this case, since the temperature of the products is assumed to be the boiling temperature, 373 K, one does not have to assume constant specific heats. Changes in thermal enthalpy can be found in the ideal gas tables in (Annamalai and Puri, 2004). These thermal enthalpies are listed in Table V.6 along with other common parameters that will be used during this chapter.

Table V.6. Required parameters for model analysis.

	Enthalpy of Formation (kJ/kmole)	Specific Heat* (kJ/kmole/K)	Specific Heat** (kJ/kmole/K)	Changes in Thermal Enthalpy @ 373K (kJ/kmole)
Oxygen, O2	0	32.45	33.55	2,227
Nitrogen, N2	0	31.93	32.53	2,185
Carbon dioxide, CO2	-393,546	46.70	48.82	2,941
Liq. Water, H2O(l)	-285,830	38.66	42.30	--
Water Vapor, H2O(g)	-241,845	38.66	42.30	2,541
Sulfur Dioxide, SO2	-296,842	47.83	49.05	3,123
Ash (on mass basis)	--	0.8(kJ/kg/K)	0.8(kJ/kg/K)	--
Methane, CH4	-74,850	--	65.02	--

*average specific heat between 298 and 1200K
**averaged specific heat between 298 and 2000K

Plugging these values into equation (IV.21) along with (V.5) and the DAF HHV for separated solids found in Table V.3 one can obtain the following expression.

$$\left[18,616 - 515 \left(\frac{\%EA}{100} \right) \right] \%A = \left[1,861,600 - 51,502 \left(\frac{\%EA}{100} \right) \right] - \left[21,198 - 515 \left(\frac{\%EA}{100} \right) \right] \%M \quad (V.6)$$

Solving for %A provides an expression for the maximum allowable percentage of ash for a DB waste disposal system.

$$\%A_{allowed} = \frac{(1,861,600 - 515(\%EA)) - (21,198 - 5.15(\%EA))\%M}{(18,616 - 5.15(\%EA))} \quad (V.7)$$

Subsequently the required combustible percentage can be written as:

$$\%Cb_{needed} = 100 - \%M - \%A_{allowed} \quad (V.8)$$

Equations (V.7) and (V.8) are on an as received basis. To convert them to a dry basis (i.e. as a percentage of the solids in the DB), one can simply use equation (V.3). These equations are plotted in Fig. V.2a.

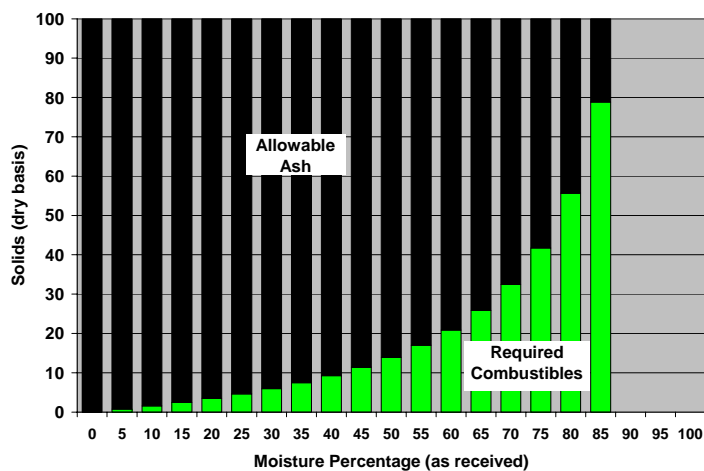


Fig. V.2a. Required solids composition to vaporization all moisture in DB fuel (10% Excess Air, dry basis).

Note, that combustibles and ash are illustrated on a dry basis (i.e. as a percentage of the dry solid content). The maximum amount of ash and the minimum amount of combustibles are shown on a dry basis as a function of the moisture percentage. In Fig. V.2b, the solids are plotted on an as received basis.

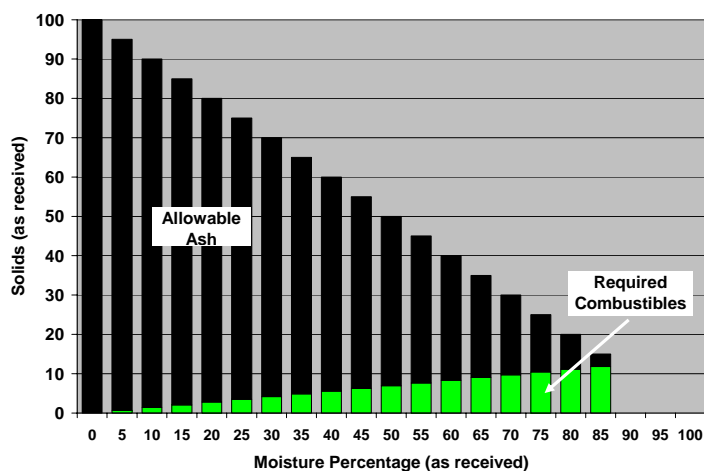


Fig. V.2b. Required solids composition to vaporization all moisture in DB fuel (10% Excess Air, as received basis).

These results can be used to determine the viability of a proposed disposal system simply by knowing the properties of the incoming DB fuel. For example, vacuumed manure is roughly 50% moisture. From the figure, 14% of the dry solids in the DB must be combustibles, while the remaining 86% can be inert ash. If these requirements are not met, then the solids will not be completely burned into gaseous products and ash, while the moisture in the products will not be fully converted to steam at 373 K.

The flushed manure can contain as much as 97% moisture. The sample taken at the Broumley Dairy was about 93% moisture. According to Figs. V.2a and V.2b, DB with moisture contents of 90% or higher cannot be fully combusted even when no inert ash is present in the fuel. Hence, one can see that the proposed systems for flushed manure disposal will not meet the primary objective set in chapter 3 without firing additional fuel.

As an illustration, consider the overall direct firing system for flushed manure in Fig. IV.7. If one were to draw a control volume that encompassed everything except the dairy farm and the process, then the inputs and outputs for the system would be virtually the same as those in Fig. V.1. Therefore, thermodynamically, it is not possible to meet the objective for DB fuels with extremely high moisture percentages, especially if these fuels also have high ash contents on a dry basis.

In Fig. V.3, the required combustible percentage is plotted against moisture percentage for 10% and 100% excess air. However, excess amounts of air seem to have little effect on the requirements.

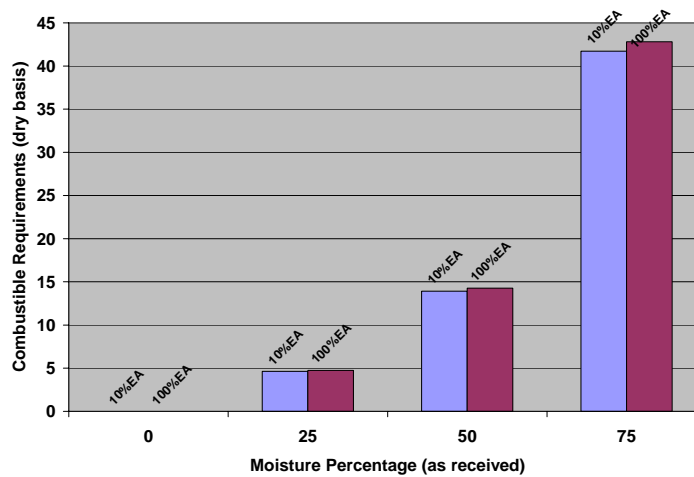


Fig. V.3. Excess air effects on combustible requirements for producing $H_2O(g)$ in products of combustion at 373K.

Aside from the requirements of Model I and Fig. V.1, there is also a requirement on flame temperature. The preheated-air combustors in Model II are designed to meet the flame temperature requirement. The results for Model II will be discussed presently.

Results and Discussion of Model II

Since it was found that DB fuel with extremely high moistures cannot be directly fired, it will be assumed that separated solids (not flushed manure) will be fired in Model II. Yet, from Table V.1, separated solids still contain 81% moisture, which still may be too high. Therefore, the goal of the present analysis should be to determine how much the moisture percentage must be reduced to fire separated DB solids at flame temperatures greater than or equal to a prescribed minimum value. As discussed earlier, this minimum temperature will be assumed to be 1200 K. Note that, since the first law must satisfy control volumes 1, 2, 3, and 4 in Figs. IV.2 and IV.3, the results for both of

these systems (parallel flow and counter flow heat exchangers), as far as minimum combustible requirements (or maximum moisture percentages), will be the same.

The differences between the system with a counter flow heat exchanger and the system with a parallel flow heat exchanger are the assumptions made during the analysis. Therefore, the results and discussion will be largely influenced by these assumptions.

a) Results for Combustor Design with Counter Flow Heat Exchanger

The results of the combustor design with the counter flow heat exchanger will first concentrate on determining the additional percentage of combustibles required to burn at 1200 K. In this way, one can determine if the 81% moisture content in the separated solids is low enough or if further dewatering processes are needed to burn at the prescribed flame temperature of 1200K. Once the optimum moisture and ash percentage is determined, then some discussion of the heat exchanger efficiency will follow.

Begin by considering equations (IV.35) and (IV.36) that were derived for this model. Setting T_5 to 1200 K and assuming an ideal heat exchanger ($\eta_{HX} = 1$), the temperature profiles should resemble the sketch in Fig. V.4

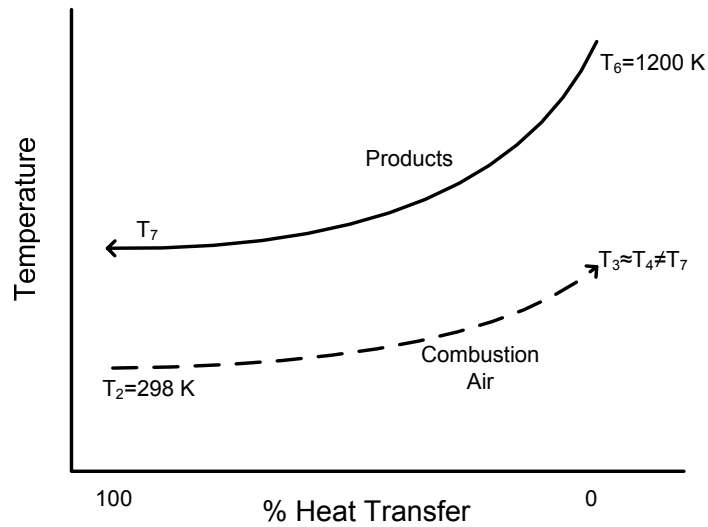


Fig. V.4. Temperature vs. %heat transfer for a counter flow heat exchanger.

Since the heat exchanger efficiency only determines the exhaust temperature T_7 , it should not matter whether or not an ideal heat exchanger is assumed or not, just so long as the efficiency is not so low that heat transfer will not occur. For each value of ash percentage, %A, one can iterate the moisture percentage, %M, so that the conditions in equation (IV.36) are barely met. Subtracting %M and %A from 100% would give the minimal combustible percentage, %Cb to burn at 1200 K. The results of this iteration are shown in Fig. V.5.

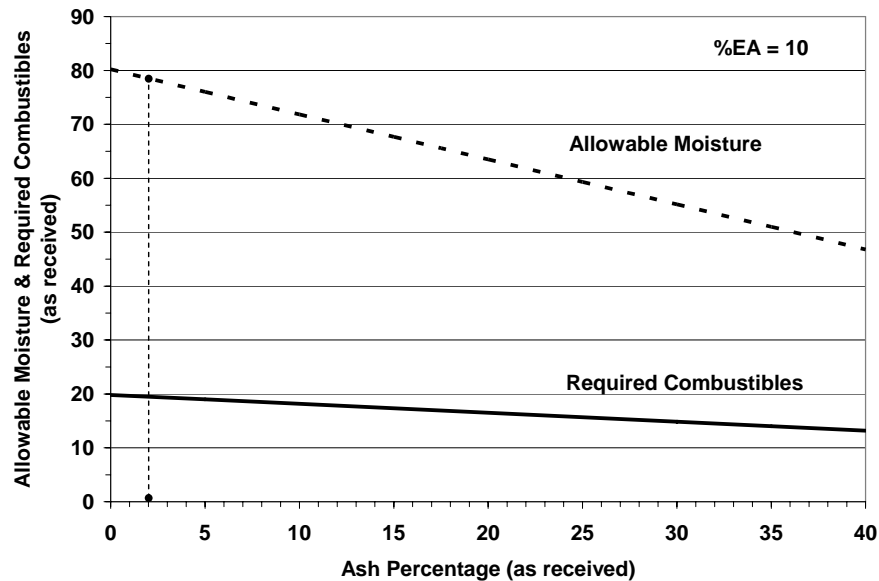


Fig. V.5. Allowable moisture & required combustible percentage to burn dairy biomass @ 1200 K (1700 deg F) using preheated-air combustor with counter flow heat exchanger.

The solids coming out of the separator were found to have a moisture percentage of about 81% and an ash percentage of about 2% (10% on a dry basis) according to the results of the sample taken at the Broumley Dairy. See Tables V.1 and V.2. As previously discussed, the preheated-air combustor should increase flame temperatures. However, it becomes clear that 81% moisture is just slightly too high. In Fig. V.5, the vertical dashed line at 2% ash indicates that about 79% moisture is the maximum amount of moisture allowable to burn at 1200 K. In reality, even 79% moisture may be optimistic, since there were assumptions about the heat exchanger being adiabatic and that losses in the pipe were minimal. In any case, the moisture in the separated DB must be lowered before firing.

One option is to use an auger press as described in (Young and Pian, 2003) that lowers the moisture in the solids to about 70%. This is illustrated in the schematic of the

proposed disposal system for flushed manure (Fig. IV.7). Assuming that the ash on a dry basis stays the same as the solids are processed in the auger, the DB solids coming out of the auger would be composed of 70% moisture, 3% ash, and 27% combustibles. According to Fig. V.5, DB with 3% ash can have as much as 77% moisture and still burn at 1200 K, hence the auger would be an acceptable solution for reducing the moisture content in the DB solids.

In comparing these results to the results of Model I, Figs. V.6a and V.6b (shown below) may make more sense. Ash and combustible percentage are indicated on a dry basis. Therefore, DB solids pressed in an auger are 70% moisture and still 10% ash on a dry basis, which is more than adequate since 70% moisture DB can contain up to 41% ash(dry) and still be fired at 1200 K (Fig. V.6a).

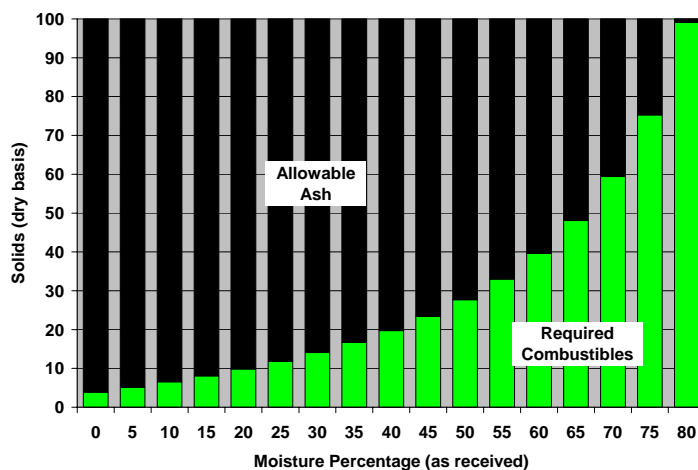


Fig. V.6a. Required solids composition to burn dairy biomass @ 1200 K (1700 deg F) using a preheated-air combustor (dry basis).

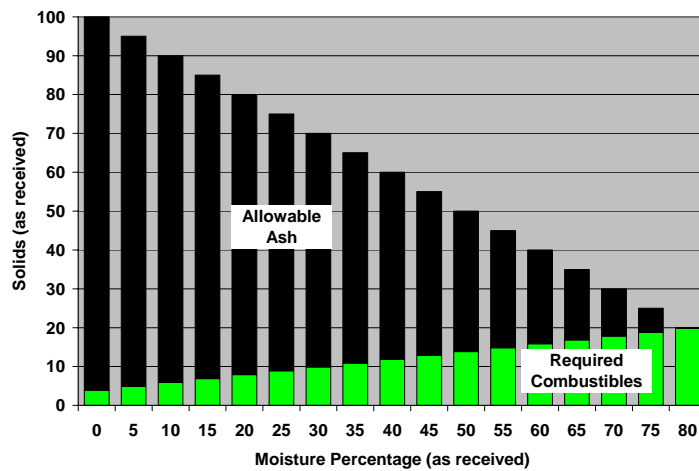


Fig. V.6b. Required solids composition to burn dairy biomass @ 1200 K (1700 deg F) using a preheated-air combustor (as received basis).

With these Figures, it is easier to see the additional combustible requirements for burning at 1200 K. As expected, these requirements are greater than those from Model I, which only required that all moisture in the fuel be vaporized by the heat released by the combustibles. However, for the present case, the combustibles have to produce enough heat to vaporize all the moisture and additionally enough heat to raise the exhaust product's temperature to 1200 K. Table V.7 further illustrates this point by listing the combustible requirements for vaporizing the moisture, burning at 1200 K with a heat exchanger, and burning at 1200 K without a heat exchanger.

The results of Model I are shown in the second column for comparison, along with the required combustible percentage to burn at 1200 K without a heat exchanger.

Table V.7. Combustible requirements for vaporizing moisture content vs. requirements for burning at 1200 K.

%M	10% Excess Air		
	%Cb needed to vaporize all moisture in DB fuel	%Cb needed to burn at 1200 K w/ heat exchanger	%Cb needed to burn at 1200 K w/o heat exchanger
0	0.00	3.92	6.53
10	1.39	5.91	9.84
20	2.78	7.90	13.14
30	4.17	9.88	16.45
40	5.56	11.88	19.74
50	6.95	13.85	23.05
60	8.34	15.84	26.36
70	9.74	17.82	29.67

At higher moisture contents, the difference between the combustible requirements of vaporizing the moisture and the requirements of burning at 1200 K increases. Furthermore, it seems at low moisture contents, the payoff of having a heat exchanger is not very substantial. For example at 10% moisture, the combustible requirement is reduced by only 3.93% by using a heat exchanger. However, at 70% moisture, the combustible requirement is reduced by 11.85%.

For the present case, since the ash in the separated DB solids is about 10%(dry), and it is assumed that the press will reduce the moisture content to 70%, a heat exchanger may be needed as a necessity, because only about 27% combustibles will be present in the fuel. Yet, according to the results in Table V.8, 29.67% combustibles would be needed to burn at 1200 K without a heat exchanger.

Additionally, one can use equations (IV.35) and (IV.36) to compute the exhaust temperature, T_7 , the preheated air temperature, T_3 , and the minimum required heat exchanger efficiency and effectiveness for varying moisture percentages of the DB separated solids. These results are listed in Table V.8 for separated DB solids (10% ash(dry)) burning at a flame temperature of 1200 K and 10% excess air.

Table V.8. Results for combustor design with counter flow heat exchanger.

%M	Exhaust Temp, T7 (K) @ 100% Heat Exchanger Efficiency	Required Preheat Temp, T4 (K)	Minimum Heat Exchanger Efficiency (%)	Required Heat Exchanger Effectiveness (%)
68	1195	308	1	1
69	1163	368	5	8
70	1130	423	8	15
71	1095	500	12	22
72	1060	574	16	31
73	1024	652	20	39
74	986	737	24	49
75	947	829	29	59
76	906	928	33	70
77	864	1036	39	82
78	820	1153	43	95
78.36	804	1198	44	100
Results for DB fuel with 10% ash(dry basis), 10% excess air, 1200K Flame Temperature				

Notice that the results only cover a range of 68% to 78.36% moisture. If the moisture percentage were lower than 68%, then a heat exchanger would not be required to burn at 1200 K (assuming 10% ash(dry)). This can be seen in the second column, which lists the exhaust temperature for 100% heat exchanger efficiency. At 68% moisture, the exhaust temperature is very nearly 1200 K. Also, if the moisture percentage is higher than 78.36%, then the required preheat temperature would be higher than the flame temperature, which would violate the second law during the heat transfer in the heat exchanger. In essence, 78.36% moisture is the maximum allowable moisture percentage to burn at 1200 K.

The values in the third column, which lists the minimum heat exchanger efficiency, are computed by iterating lower values of efficiency until the conditions in equation (IV.36) are violated. At the minimum heat exchanger efficiency, the temperature of the exhaust will only be slightly higher than the ambient 298 K.

These calculations are valuable because they gauge what range of moisture percentages of separated DB solids are appropriate for using a preheated combustor design with a counter flow heat exchanger. They also show the minimum design requirements of the heat exchanger, as far as its efficiency and effectiveness. However, in practice, it is best to have as high of efficiency as possible in order to use the remaining heat in the product's stream for additional processes. This leads to the discussion of Model III, which replicates the use of the remaining heat in the exhaust to vaporize the remaining moisture from the flush, not included in the separated solids (see Fig. IV.7). However, first a brief discussion will follow about the idealized combustor design with the parallel flow heat exchanger.

b) Results for Combustor Design with Parallel Flow Heat Exchanger

The results for the parallel flow heat exchanger should be approximately the same as the counter flow heat exchanger since in both systems, prescribing the flame temperature to be 1200 K (i.e. $T_5=1200$ K), constrains the system.

For the parallel flow heat exchanger, the temperature of the exhaust products exiting the exchanger was assumed to be equal to the temperature of the preheated combustion air entering the combustor. In effect, the heat exchanger was assumed to be adiabatic with the temperature profiles of the products and the combustion air resembling those shown in Fig. V.7

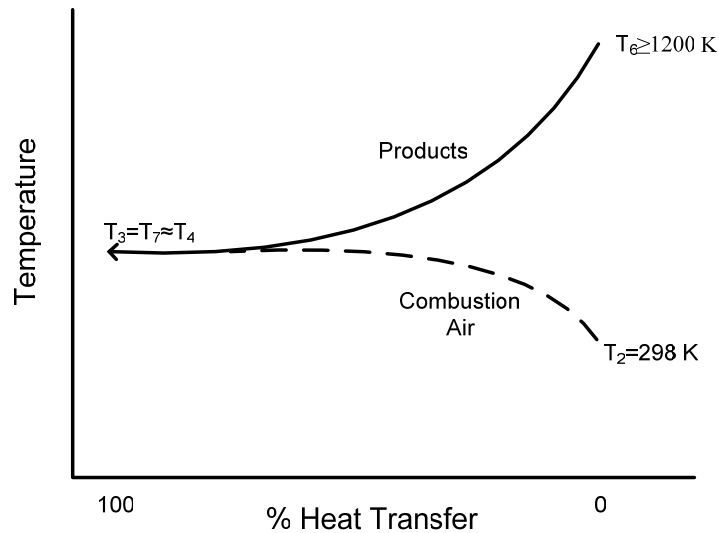


Fig. V.7. Temperature vs. %heat transfer for a parallel flow heat exchanger.

However, note that this is an ideal case. Even for a parallel flow heat exchanger, these temperatures may not equilibrate. However, by putting this additional constraint on the system, one can find a particular solution to the problem (i.e. the particular values of $%M$ and $%A$) that satisfies this idealized condition.

The analysis begins by plugging equation (V.5) into (IV.40) and setting T_5 to 1200 K. This should produce a quadratic equation in terms of $%M$, $%A$, and $%EA$ for firing separated DB solids in the preheated-air combustor with a regenerative parallel flow heat exchanger. Then, for different values of $%A$ and $%EA$, maximum allowable moisture percentages can be computed. Furthermore, using equation (V.1) one can then compute the required combustible percentage. The results of this rather elaborate process are shown in Fig. V.8.

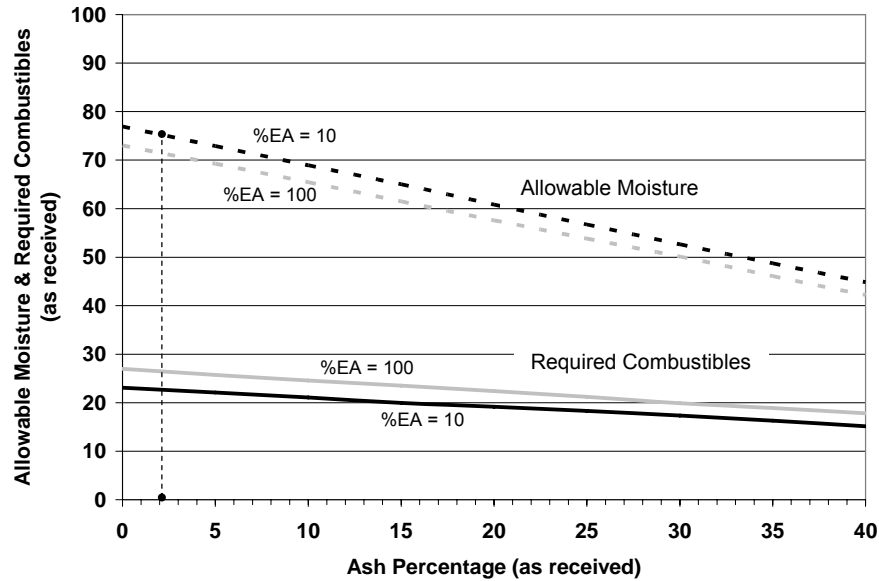


Fig. V.8. Allowable moisture & required combustible percentage to burn dairy biomass @ 1200 K (1700 deg F) using preheated-air combustor with ideal parallel flow heat exchanger.

As one can see, the allowable moisture is slightly less for DB solids with 2% ash (vertical dotted line) when fired in this ideal preheated combustor design (compare with Fig. V.5). Therefore, the combustible requirement is actually slightly higher in order to meet the assumption of $T_7 = T_4$. This is further demonstrated in Table V.9, and as one can see, for each value of moisture percentage, slightly more combustibles would be required to burn DB in the preheated combustor with the idealized parallel flow heat exchanger.

Table V.9. Combustible requirements for counter flow heat exchanger vs. idealized parallel flow heat exchanger.

%M	10% Excess Air	
	%Cb needed to burn at 1200 K w/ counter flow heat exchanger	%Cb needed to burn at 1200 K w/ idealized parallel flow heat exchanger
0	3.92	4.92
10	5.91	7.45
20	7.90	9.48
30	9.88	11.94
40	11.88	14.20
50	13.85	16.60
60	15.84	18.96
70	17.82	21.33

Results and Discussion of Model III

From the results of Model II, it was concluded that the separated DB solids fired in the combustor should be pressed to 70% moisture, 3% ash and 27% combustibles (10% ash and 90% combustibles on a dry basis). Now one can discuss how much of the unclean water can possibly be vaporized from the remaining heat in the exhaust leaving the heat exchanger. Recall that the results from Model I have already shown that not all of the unclean water from the separator will be vaporized, due to the fact that the flushed manure exiting the dairy and entering the system at the separator is probably over 90% moisture (see Fig. IV.7), and from Fig. V.2a and V.2b, it can be seen that for DB with over 90% moisture, no amount of combustibles can release the required heat to vaporize the unclean water.

First, consider equation (IV.42) which models the boiler efficiency of separated DB solids for different values of exhaust flue gas temperature and excess air. Boiler

efficiency curves generated from this equation are presented in Fig. V.9 for pressed DB solids.

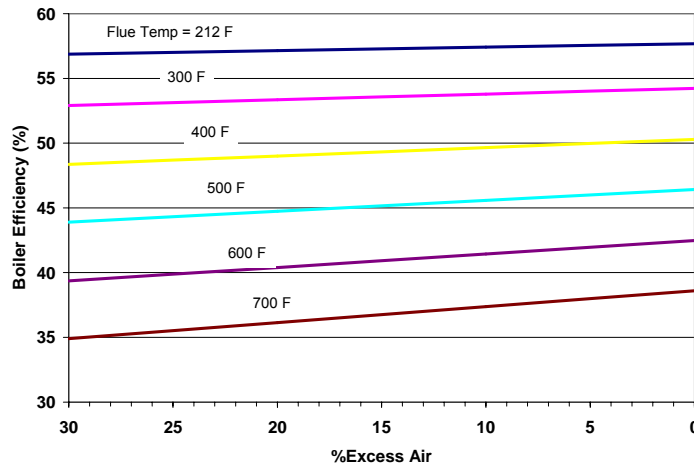


Fig. V.9. Boiler efficiency curves for separated DB solids (70% moisture, 3% ash, 27% combustibles).

In order to maximize the amount of heat transferred to the unclean boiler water, burning at 10% excess air is recommended. However, in practice, solid fuels are usually burned at 20 or 30%EA. On the other hand, burning richer than 10%EA (i.e. with lower excess air) may lead to unburned fuel.

If detailed work is done on the process in Fig. IV.7, then a steam flow rate will be prescribed, and an energy balance of the boiler chamber would lead to an ideal exhaust flue gas temperature (T_8 in Fig. IV.4). However, in the current study it is difficult to say what the exhaust flue gas temperature will be, unless it is assumed that the exhaust temperature is equal to the temperature of the steam being produced from the unclean water. For the duration, this assumption will be made.

It is desired to obtain values for the disposal efficiency (equation (IV.45)) in terms of the moisture percentage of the flushed manure, while continuing to assume that pressed DB solids (70%M, 2%A, and 27%Cb) are being fired in the combustor. With equation (IV.41) one can find the heat available to the unclean boiler water.

Next, the states of the water entering and leaving the boiler must be determined. To do so, consider Fig. IV.5. Suppose 100 psi saturated steam is required for the process. The water must first be pumped to this pressure. This is further illustrated on the temperature-entropy diagram also in Fig. IV.5. At state 9, properties can be found in the steam tables in (Moran and Shapiro, 2000), $P_9 = 1.01\text{bar}$, $T_9 = 298\text{K}$, and $v_9 = 0.00104\text{ m}^3/\text{kg}$, $h_9 \approx u_{f,9} = 104.88\text{ kJ/kg}$. Where u is the internal energy and v is the specific volume of the water. The internally reversible pump work can be calculated as:

$$\begin{aligned} \left(\frac{W_p}{m_w} \right)_{rev} &= v_9 (p_{10} - p_9) \\ &= .00104 \frac{\text{m}^3}{\text{kg}} (689 - 101) \frac{\text{kN}}{\text{m}^2} = 0.588 \frac{\text{kJ}}{\text{kg}} \end{aligned} \quad (\text{V.9})$$

Now finding the isentropic enthalpy at 10:

$$\begin{aligned} h_{10s} &= \left(\frac{W_p}{m_w} \right)_{rev} + h_9 \\ &= 0.588 \frac{\text{kJ}}{\text{kg}} + 104.88 \frac{\text{kJ}}{\text{kg}} = 105.47 \text{ kJ/kg} \end{aligned} \quad (\text{V.10})$$

If one assumes the pump has an efficiency of 85%, then the actual enthalpy at 10 may be found with the following:

$$\begin{aligned}
 h_{10} &= \frac{h_{10s} - h_9}{0.85} + h_9 \\
 &= \frac{105.47 - 104.88}{0.85} + 104.88 = 105.57 \text{ kJ/kg}
 \end{aligned}
 \tag{V.11}$$

Next, one may look up the state of the saturated steam at 100psi (6.89bar) ($T_{11} = 437\text{K}$, $h_{11} = 2762.76 \text{ kJ/kg}$).

Now, the only remaining unknown in equation (IV.45) is the resulting mass (or volume) of the unclean water per 100 kg of as received DB fuel fired in the combustor, m_w . Moreover, this variable can be expressed in terms of the moisture in the original stream of flushed manure exiting the free stalls to the separator. See equation (IV.44) where, for the present example, $\%M_{solids} = 70\%$.

The moisture percentage in the flushed manure, $\%M_{flush}$, is one of the largest factors in determining how much unclean water may be vaporized. Equation (IV.44), can be used to compute the mass (volume) of the unclean water left after the solids are separated and pressed. From this equation, one can produce Fig. V.10 which illustrates the gallons of unclean water per 100 lbs of pressed DB fired. Note that the density of the unclean water was assumed to be $1,000 \text{ kg/m}^3$ and that 1 m^3 is approximately 264 gallons. One kg is approximately 2.2 lbs.

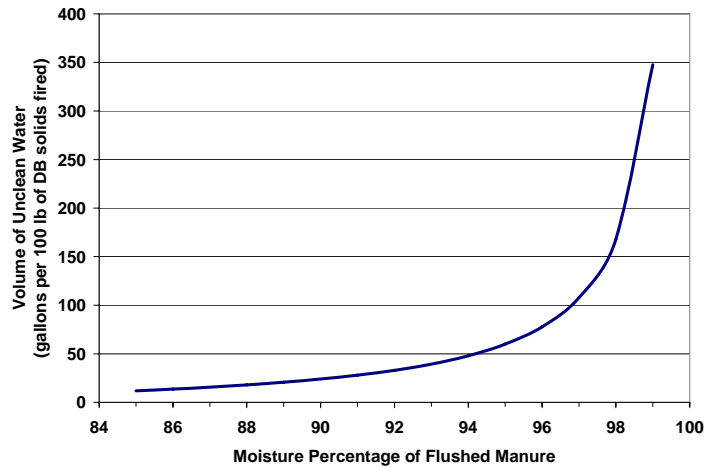


Fig. V.10. Volume of unclean water vs. moisture percentage in the flushed DB manure.

The amount of unclean water increases sharply as the moisture percentage in the flush increases. Thus, it is recommended that farmers use less water while flushing their stalls. Reducing the moisture percentage from 95% to 88 or 90% greatly improves the effectiveness of the flushed DB disposal system. This can be illustrated further by plotting equation (IV.45). See Fig. V.11, where disposal efficiency is plotted for 100 psi as well as three other boiler pressures.

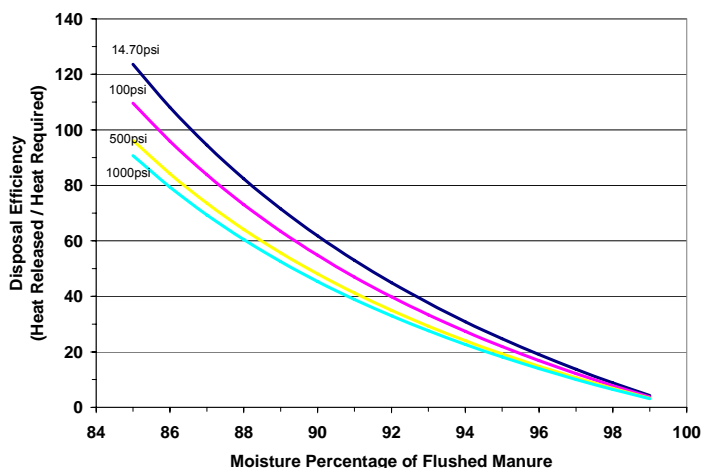


Fig. V.11. Boiler system disposal efficiency vs. moisture percentage in the flushed manure.

As explained earlier, the disposal efficiency for this study is defined as the heat released by the fired DB solids, divided by the heat required to fully convert the unclean water to steam. As expected, this efficiency greatly improves as less water is used to flush the manure. The efficiency also decreases slightly with boiler pressure because it was assumed that the exhaust temperature was the same as the saturation temperature of the exiting steam.

However, if it is found that flush water cannot be decreased, then there is another option to improve disposal efficiency. Additional solids from composts, open lots, or feedlots as well as other conventional fuels such as coal and methane can be blended with the separated solids. This would reduce the moisture percentage of the fired fuel and increase the combustible percentage; thus increasing the boiler efficiency and the disposal efficiency. As an example, assume once again that 100 psi steam is required for a process, thus making the exhaust and saturation temperatures 437 K (327 °F). The

moisture percentage of the flush, $\%M_{flush}$ will be the same as that found in the flushed manure sample at the Broumley Dairy (93.31%), and 10% excess air will be used in the combustor. Fig. V.12 shows how the boiler efficiency improves as different additional fuels are blended with the separated DB solids.

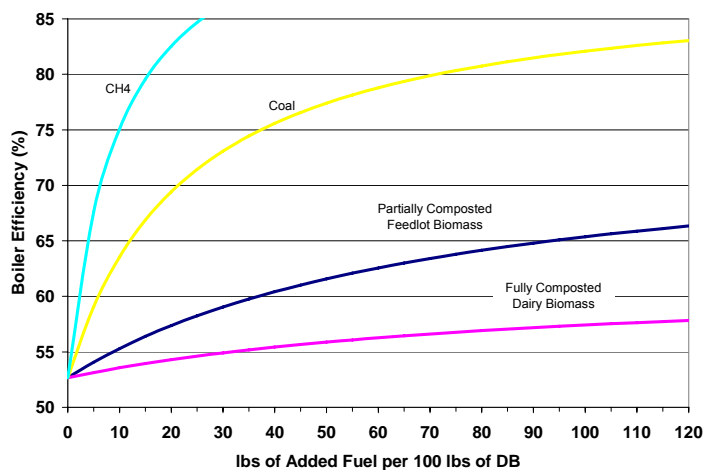


Fig. V.12. Boiler efficiency improvements while blending fuels with separated DB solids.

The improvements in boiler efficiency depend greatly on how much moisture is in the added fuel. The fully composted DB sample taken at the Broumley Dairy still had about 57% moisture (see Table V.1), whereas the partially composted feedlot biomass sample was taken from an ultimate analysis in (Sweeten, Annamalai, et al., 2003) and had a moisture content of 32%. The coal sample (15.2% moisture) was also taken from (Sweeten, Annamalai, et al., 2003) and CH₄ is assumed to be dry methane. As expected, coal and methane tend to be better candidates as blended fuel as far as performance; however, the additional costs of such fuels may become an issue. Therefore, the ideal

blends may be of separated DB solids and relatively dry composted manure from feedlots or open lots. Solar drying may also be employed to dry the composted manure. As more additional fuel is added to the blend, the boiler efficiency will come closer to the boiler efficiency of the additional fuel if it were fired alone.

Finally, disposal efficiency is plotted in a similar way in Fig. V.13

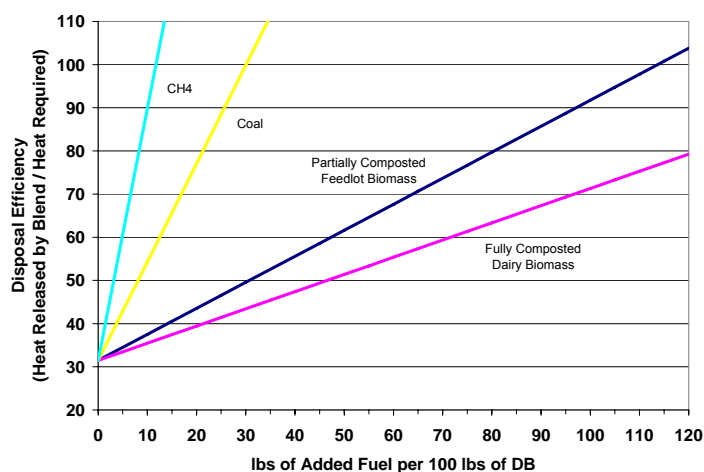


Fig. V.13. Disposal efficiency improvements with blending fuels with separated DB solids.

For our example, a 1:1 blend (i.e. 100 lbs per 100 lbs of DB) of partially composted feedlot biomass and separated DB solids would almost provide sufficient heat to vaporize all of the unclean water in the boiler chamber (91%). This would improve for lower boiler pressures. A similar blend of fully composted dairy biomass with separated DB solids would only achieve a disposal efficiency of about 71%. Furthermore, relatively little coal or methane would be required to achieve an efficiency of 100%: 30:100 blend for coal and 12:100 blend for methane. Yet, it seems that the most

effective way of improving disposal efficiency is to use less water in the flush or to collect the DB in an entirely different way. This leads to the discussion of the disposal system for vacuumed manure.

Results and Discussion of Model IV

In the context of designing these waste disposal systems, it may seem obvious to switch from a flushed system to vacuuming, however, there are a few reasons why many large dairies use flushing systems. The main reason is that flushing systems are typically automated and probably require much less labor than scraping or vacuuming. For dairies with over 1000 cows, vacuuming manure from the free stalls every day may be difficult. Furthermore, frequent flushing creates cleaner facilities and less odor problems (Fulhage, 2005). Vacuum machines may not be able to collect wet, residual manure, making the facility less sanitary.

However, if farmers can find a feasible way of replacing a flushing system with a vacuum system, then directly firing the DB becomes a matter of producing enough manure to fuel a competitive power plant. As stated earlier, one can compare the power output of this system to a plug flow digester system (100 kW from 700 cows, 0.143 kW/cow). However, as will be seen presently, the required firing rate for a vacuumed manure disposal system will greatly depend on the ash and moisture content of the vacuumed DB. Literature estimates of the moisture and ash content in vacuumed manure are used in the analysis and presentation of results.

In (Matthews, et al., 2003), the moisture percentage of vacuumed manure is approximately 50%, but given that DB is 88% moisture as excreted, this moisture

percentage can easily be higher. Therefore, the following plots of DB firing rates (which may be calculated from equation (IV.49)) will be made against %M and %A, as well as plant efficiency, which is also defined in equation (IV.49). Since boiler efficiency of a DB firing system may be low, the overall plant efficiency can also be expected to be lower than usual. Calculations are made for 15%, 25%, and 35% plant efficiencies.

On average, about 33 lbs of DB is produced per cow per day (15 kg/cow/day) in the free stalls (Fulhage, 2005). Note that this is excreted manure plus bedding on the free stall ground. If the manure is flushed, then the average volume (mass) of DB waste is considerably greater. Also, this rate is based on an overall average of DB produced by a dairy farm. Larger cows will probably produce more, while smaller cows will produce less. However, for the current study, this rate is sufficient to make comparisons to computed vacuumed manure firing rates. Hence, the approximate manure production can be estimated for a given farm as seen in Table V.10.

Table V.10. Estimated DB production and dairy size.

Dairy Size (# of cows)	DB Production lb/minute
100	2.29
300	6.87
500	11.45
700	16.03
1000	22.90
1500	34.35
2000	45.80

These production numbers can be compared to the firing rates calculated in Fig. V.14 and V.15 below. The dotted horizontal lines, for example, in Fig. V.15, indicate the DB production rates for a 300 cow, a 700 cow, and a 1000 cow dairy.

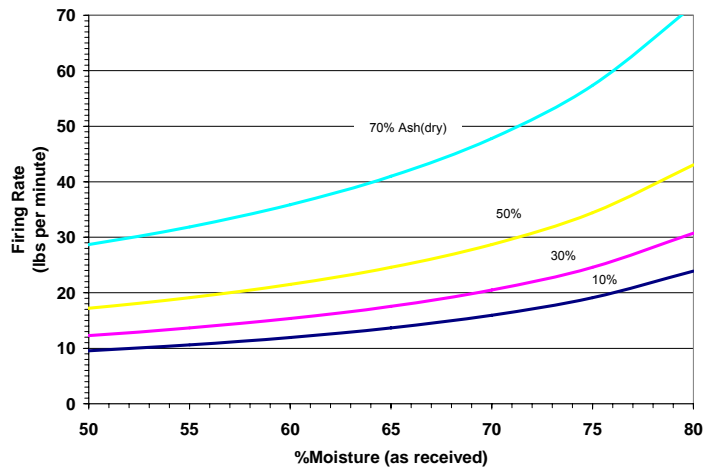


Fig. V.14. Vacuumed DB firing rate for 100 kW plant (15% plant efficiency).

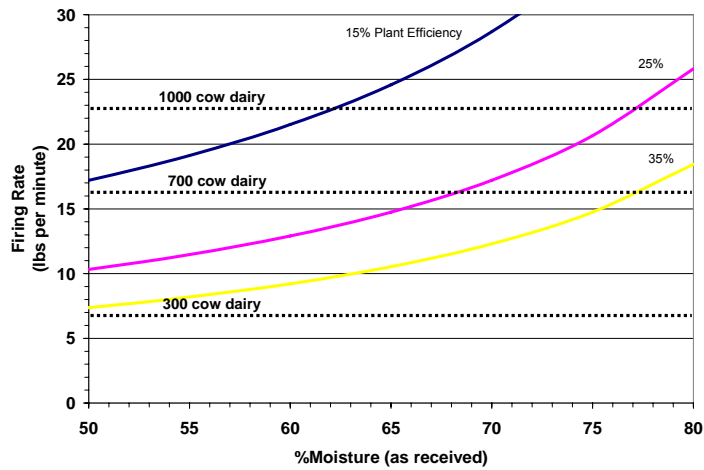


Fig. V.15. Vacuumed DB firing rate for 100 kW plant (50% ash (dry)).

From the figures, it is clear that both moisture and ash percentage greatly affect the required firing rate for this system to be competitive. Since the moisture content of vacuumed manure is probably between 50 and 80%, in Fig. V.14 it is clear that the ash percentage in the DB cannot be too high if the plant is only 15% efficient. If over 70% of the solids (i.e. 70% dry) are ash, then the required firing rate quickly becomes unattainable. However, this is probably the worst case scenario. Over 1000 cows would be needed to produce enough DB to maintain a 15% efficient plant firing solids that are 70% ash in DB that is between 50 and 80% moisture. Unfortunately, dairies of this size typically require automated flushing systems to keep their labor costs down.

On the other hand, suppose that the ash percentage of the DB is only 50%(dry) as in Fig. V.15. A 300 cow dairy could not support a 100 kW plant. However, if the plant efficiency can be increased to about 25%, then dairies between 700 and 1000 cows can possibly produce enough manure to power a competitive power plant. For the farmer, the critical object is to apply an optimum amount of bedding to the excreted manure in the free stalls so that the moisture content is lowered but the ash content stays reasonable (i.e. approximately 50%(dry)). Also, the vacuumed DB must be about 70% moisture in order to keep the flame temperature in the combustor above 1200 K. Otherwise it will have to be pressed before firing. Thus, if these design requirements can be met, then a vacuumed manure disposal system could be competitive with a plug flow digester system without the need for land application and lagoons.

Results and Discussion of Model V

Many large dairies with flushing systems currently have anaerobic digesters that convert the combustible contents in the liquid manure to biogas. However, a byproduct of an anaerobic digester is high moisture effluent. This effluent still contains all of the undesirable nutrients, such as phosphorus, that were present in the flushed manure because they are not used to form the biogas. As discussed in the literature review, even systems that recycle this effluent back to the dairy free stalls as flushing water do not fully solve the problem of nutrient overloading because the nutrient concentrations simply increase within the system and eventually leak out into the environment (Johnson, Culkin, and Stowell, 2004).

Although there have been some mechanical, biological, and chemical filtration solutions (see literature review) to reducing the amount of nutrients and other contaminants in the effluent stream, the proposed combined digester and firing system introduced in the previous chapter may be an additional option for readily disposing of the effluent. See Fig. IV.9.

First some parametric studies of the maximum mole fraction of methane, X_{CH_4} , in the biogas for different values of oxygen-carbon ratio, $o = O/C$, and hydrogen-carbon ratio, $h = H/C$, in the DB combustibles will be conducted. Next, estimated biogas production will be plotted in terms of the moisture and ash percentage of the flushed DB from the dairy. Finally, disposal efficiencies will be computed for the system depicted in Fig. IV.9.

A plot of equation (IV.56), which models the estimated methane mole fraction, is shown in Fig. V.16.

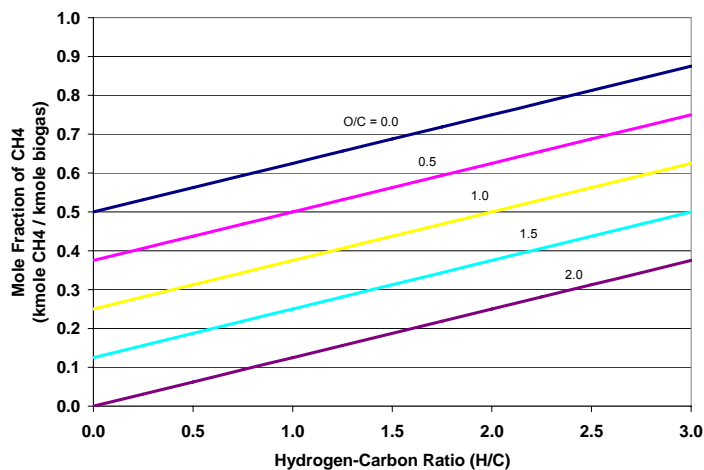


Fig. V.16. Mole fraction of methane in biogas vs. H/C and O/C ratios in flushed DB.

As expected, the methane mole fraction increases for higher hydrogen-carbon ratios, but decreases for higher oxygen-carbon ratios. As more oxygen is available in the DB, more carbon goes to making CO_2 instead of CH_4 . The mole fraction of methane does not change with different values of $\%M$ and $\%A$ in the DB because changes in moisture and ash do not change these ratios. Therefore, the quality of the biogas cannot be improved by changing manure collection techniques (i.e. reducing flushed water or vacuuming instead of flushing). However, if the combustible composition is altered, by changing the feed ratios, in such a way that H/C ratios go up while O/C ratios go down, then the amount of methane per kmole of biogas should increase, thus improving the quality of the biogas as a fuel.

With equation (IV.58), one can also plot the higher heating value of the biogas and obtain identical trends with respect to H/C and O/C ratios. See Fig. V.17.

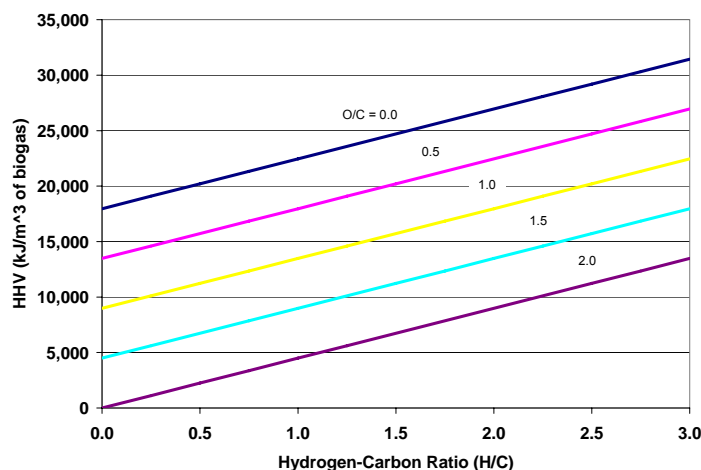


Fig. V.17. HHV of biogas vs. H/C and O/C ratios in flushed DB.

The quality of the biogas depends on the combustible composition of the DB entering the anaerobic digester; however, the theoretical maximum quantity of biogas produced per unit mass (volume) of flushed DB entering the digester varies greatly with the moisture and ash percentage in the manure. In Fig. V.18, equation (IV.61) is plotted against %M and %A for DB containing the combustible composition of flushed DB found in Table V.3.

Recall from Tables V.1 and V.2 that the flushed DB sample from the Broumley Dairy contained 93.31% moisture and about 50% ash on a dry basis. In the figure, it can be seen that for flushed DB with these percentages, the theoretical maximum amount of biogas that can be produced is about 55 liters per kg of flushed manure.

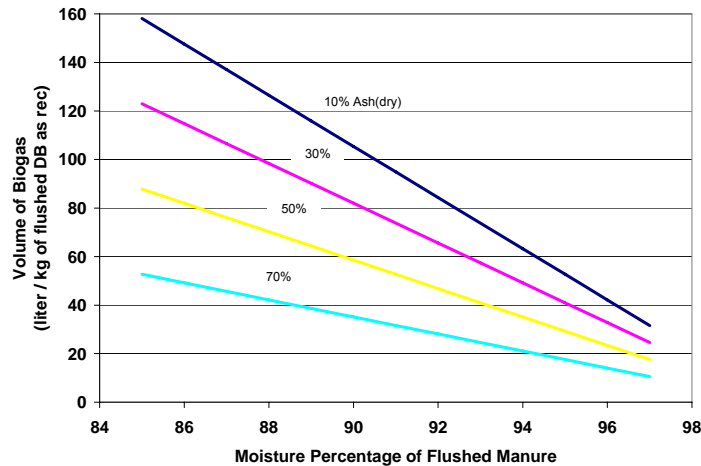


Fig. V.18. Volume of biogas vs. moisture and ash percentage in the flushed DB.

However, usually settling basins are used to remove some of the ash in the flush just before it enters the digester, and as can be seen in the figure, lowering the ash percentage greatly improves the yield. Although notice that these numbers are theoretical maximums because not all of the combustibles will be converted to biogas. The present model assumes that the remaining combustible solids in the effluent will be composed of only nitrogen and sulfur, but depending on how efficiently the microorganisms and bacteria in the digester produce CO_2 and CH_4 , the remaining solids could contain a fraction of the carbon, hydrogen, and oxygen in the original flushed DB steam.

Finally, if one recalls Fig. IV.9, in which a proposed combined digester and firing scheme is shown, the importance of producing higher yields of biogas becomes clearer. As the moisture percentage in the flushed DB increases, not only does the biogas yield decrease, but the amount of unclean water that must be vaporized increases. The dependence of disposal efficiency on the moisture and ash percentages of the flushed DB is illustrated in Fig. V.19.

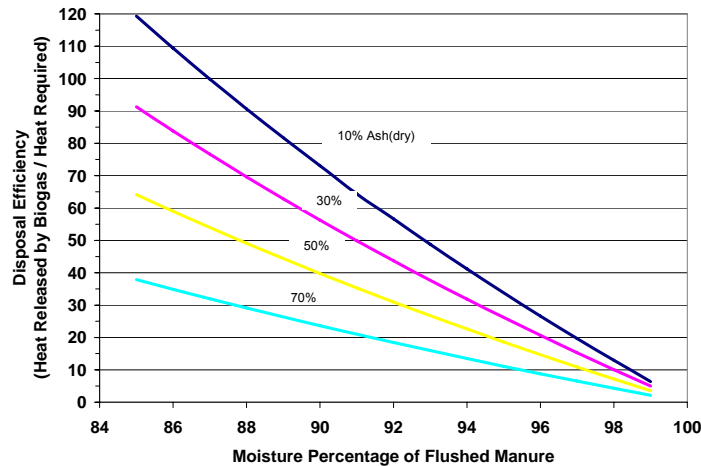


Fig. V.19. Disposal efficiency vs. moisture and ash percentage in the flushed DB (producing 100 psi saturated steam).

In order to compare this system's disposal efficiency with the disposal efficiency of Model III, 100 psi saturated steam will once again be assumed to be required for a process, and all assumptions about the boiler will remain the same.

As one can see, the results are very similar for the two models. One major difference, however, is the larger dependence on ash percentage of the current digester model. This is because in Model III, all solid material was assumed to be fired in the combustor eventually by entering with the separated and pressed solids or by being removed from the boiler chamber and being cycled back to the combustor. See Fig. IV.7. In contrast, the digester model considers only the biogas that is produced by the combustibles to be fired in the combustor. Hence, when ash percentages are high and biogas yield is low, less heat is generated to vaporize the unclean water.

Furthermore, in Model III, a relatively large amount of low quality fuel (separated solids) was burned to vaporize a relatively small amount of unclean water.

However, in the current model a relatively small amount of higher quality fuel is burned to vaporize a relatively larger amount of unclean water. The fraction of the total mass of the flushed manure that gets converted into biogas is minute compared to the fraction of the total flushed manure that gets separated and fired in the combustor because 70% of the separated and pressed solids are moisture. Therefore, the disposal efficiencies of Models III and V tend to be approximately the same for similar ash and moisture percentages of the incoming flushed manure.

Moreover, this similarity in disposal efficiency can be predicted by Model I, since thermodynamically the specifics of the processes involved in the system are not important. The disposal plan depicted in Fig. IV.7 has the same inputs and outputs as the disposal plan shown in Fig. IV.9. However, in reality, Model III may be more reliable due to the inherent dependence that the digester model has on the biological processes involved in anaerobic digestion. Presumably a mechanical separator and auger press should provide a more consistent supply of fuel (albeit a lower quality fuel) to the boiler system than a biological digester.

CHAPTER VI

CONCLUSIONS

1. On a dry, ash free basis (DAF) the combustible content and the higher heating value of dairy biomass (DB) is very similar to that of feedlot biomass (FB) and other cattle manures. Nearly all of the modeling and results presented in this study can be applied to other cattle manures to a fairly good approximation.
2. The moisture content of DB is extremely high even for partially and fully composted samples due to using flushing as a collection method, although the ash content of these samples is fairly low. Moreover, the ash percentage of flushed manure is surprisingly high at 51% on a dry basis, even though composted manure was used as bedding instead of sand or straw at the dairy where the samples were taken.
3. In Model I, where a simple direct firing system was presented, the minimum combustible percentage to fully burn DB and generate gaseous products of combustion at 373 K with all moisture as vapor was found to vary linearly with moisture percentage. When the DAF values for separated solids are used, the minimum required combustible percentage for a 70% moisture fuel was approximately 9% (as received).
4. For DB with moisture percentages 90% or higher, no amount of combustibles can vaporize all the moisture and generate products of combustion at 373 K.
5. For Model II, it was found that when using a preheated air combustor with a regenerative type heat exchanger, the maximum allowable moisture percentage for

separated DB solids (10% ash (dry)) to be fired at 1200 K was found to be approximately 79%.

6. However, since there were assumptions about the preheated air combustor system being adiabatic, in practice, it is recommended that an auger or screw press be used to further reduce the moisture percentage to 70% before directly firing the separated solids.
7. Furthermore, since the separated DB solid sample was found to have a moisture percentage of about 81%, further dewatering processes would need to be utilized before firing, irregardless of any assumptions made during the modeling.
8. For the ideal preheated air combustor with a parallel heat exchanger that allowed the temperature of the combustion air to equilibrate with the temperature of the exhaust products, the minimum required combustible percentage was found to be slightly higher than the combustor with the counter flow heat exchanger.
9. In Model III, the boiler efficiencies for firing separated DB solids were found to be quite low due to the fact that the combustibles must first generate enough heat to vaporize the moisture in the fuel before supplying any heat to the boiler water.
10. One of the most effective ways to increase the disposal efficiency of the waste disposal system for flushed manure is to lower the amount of water used in the flush.
11. Since the steam generated from vaporizing the unclean separated water may be impure, the steam may only be suitable for certain thermal process, and not for generating power in a steam turbine.

12. In order to achieve disposal efficiencies of 100%, a 1.15:1 blend of partially composted feedlot manure and separated DB solids could be fired in the boiler system.
13. The most appropriate blending fuels are composted cattle manures with relatively low moisture contents, although conventional fuels such as coal could also be used more effectively if economic restrictions allow them.
14. In Model IV, it was found that since vacuumed manure solids are not required to vaporize any unclean separated water, the heat generated from directly firing vacuumed manure can be used to generate steam to run a vapor power steam cycle and produce electricity.
15. It may be possible to install a competitive vacuumed manure firing system on a mid-sized dairy (700-1000 cows) that is small enough to switch from a flushing system to a vacuumed system and large enough to produce sufficient fuel rates of DB solids.
16. In Model V, it was found that the mole fraction of CH_4 in biogas generated in an anaerobic digester increases with higher H/C ratios and decreases with higher O/C ratios.
17. The yield of biogas per unit mass (volume) of as received flushed DB depends heavily on both the moisture percentage and the ash percentage in the DB.
18. Disposal efficiencies for a combined digester and firing system were found to be very similar to the disposal efficiencies of the system in Model III.

19. To a fairly good approximation, Model I can be used to evaluate any of the disposal systems or schemes in this study without knowing the specifics of the actual processes involved in the system.

CHAPTER VII

FUTURE WORK

The following are recommendations for future work in studying thermo-chemical conversion of dairy biomass through direct firing.

- Samples of vacuumed manure should be taken in order to draw more definitive conclusions for Model IV.
- The ash content of separated DB solids seems to be low and may need to be reanalyzed. Perhaps an investigation into the screen size and characteristics of the screen solid separator used on the Broumley Dairy may be necessary. It is speculated that fibrous solids with little ash are captured in the screen while spherical solids with more ash flow with the water. This hypothesis must be checked.
- Experimentation on minimum ignition temperatures for DB solids may provide more accuracy and realistic results to the models instead of simply assuming a minimum required flame temperature of 1200 K.
- This study focused on the combustion side of the boiler system; however, little analysis was given on how pure the steam would be when generated from unclean separated water. A study of the impurities of the steam could begin from the ash analysis, which contains the amounts of many of the species that would be present in the unclean water.
- Moreover, given the possible impurities of the generated steam and the fact that the steam may at best be saturated steam, what thermal processes on a typical dairy could possibly benefit?

- Furthermore, there ought to be future work done on the formation of agglomerates and hard deposits (in the case of DB, phosphorus reacting with sand in the inert material) on heat exchanger surfaces and general fouling in the system. According to Schmidt and Pinapati (2004), depending on the conditions of the combustion process, the products from firing biomass may have adverse effects on equipment and operation.
- A complete economic analysis of the capital and expected operation and maintenance cost should be done for each of the proposed systems, and then compared to the economics inherent to digester systems.
- It may be necessary to conduct a field study on the economics and labor requirements of using vacuums to collect manure from the free stalls. Since most dairies still either scrape manure or flush manure, it is difficult to find this information on the literature.

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APPENDIX A
NOMENCLATURE

Symbols

- a -Variable for balancing chemical reaction equation for O₂, oxygen-fuel ratio
- a_{st} -Stoichiometric oxygen-fuel ratio
- $\%A$ -Ash percentage, kg of ash / kg of as rec fuel
- b -Variable for balancing chemical reaction equation for CO₂
- c -Variable for balancing chemical reaction equation for H₂O
- $\bar{c}_{p,k}$ -Constant pressure specific heat of species k
- C -Elemental carbon, kmol C /100 kg of as rec DB
- CO_2 -Carbon dioxide
- $\%Cb$ -Combustible percentage, kg of combustible / kg of as rec fuel
- d -Variable for balancing chemical reaction equation for N₂
- DAF_k -Dry, ash free content of element k , kg of k / kg of DAF fuel
- e -Variable for balancing chemical reaction equation for SO₂
- EF -Extra fuel in blend, kg of added fuel / kg of as rec DB
- $\%EA$ -Percent excess air
- f -Variable for balancing chemical reaction equation for O₂ in products
- $\%FC$ -Percent fixed carbon
- h -Hydrogen-carbon ratio
- $h_{1,2,3,\dots}$ -Enthalpy of water at location 1,2,3,..., kJ/kg
- \bar{h}_k -Total enthalpy of species k , kJ/kmole

- $\bar{h}_{f,k}^0$ -Enthalpy of formation of species k , kJ/kmole
- $\Delta\bar{h}_{f,k}^T$ -Change in thermal enthalpy of species k at temperature T , kJ/kmole
- H - Elemental hydrogen, kmol H /100 kg of as rec DB
- H_2O -Water
- HHV_k -Higher heating value of fuel k , kJ/kg
- m -Mass, kg
- MW_k -Molecular weight of species or fuel k , kg/kmole
- $\%M$ -Moisture percentage, kg of moisture / kg of as rec fuel
- n -Nitrogen-carbon ratio
- N -Elemental nitrogen, kmol N /100 kg of as rec DB
- N_2 -Nitrogen
- N_k -Number of kmoles of species k , kmole
- N'_k -Number of kmoles of species k in digester chemical reaction equation
- o -Oxygen-carbon ratio
- O -Elemental oxygen, kmol O /100 kg of as rec DB
- O_2 -Oxygen
- P -Pressure, kN/m² or kPa
- Q -Heat transfer, kJ/kg
- s -Sulfur-carbon ratio
- S -Elemental sulfur, kmol S / 100 kg of as rec DB
- SO_2 -Sulfur dioxide
- T -Temperature, K

- u -Internal energy, kJ/kg
- v -specific volume, m³/kg
- V -Volume, m³
- w -Number of kmoles of liquid water in the as rec fuel
- W -Work or power plant capacity, kW

Greek Symbols

- ε -Heat exchanger effectiveness
- η -Efficiency

Subscript

- 1,2,..., -Location on diagram or control volume
- air* -Species in air
- f* -Formation or fuel
- (g) -Gaseous state
- in* -Into control volume
- k* -Indicates element or species
- (l) -Liquid state
- out* -Out of control volume
- p* -Constant pressure
- products* -Species in products
- (s) -Solid state
- w* -Water or to boiler water

Abbreviations

as rec -As received

CV -Control volume

DAF -Dry, ash free

DB -Dairy biomass

EF -Extra fuel

FB -Feedlot biomass

FC -Fully composted

HHV -Higher heating value

HX -Heat exchanger

PC -Partially composted

rev -Reversible

APPENDIX B

TOTAL ENTHALPY OF DAIRY BIOMASS FUEL

The total enthalpy of the DB fuel will have components from the combustibles, the liquid moisture and the inert ash. Hence, the total enthalpy can be conveyed on a molar basis with the following equation.

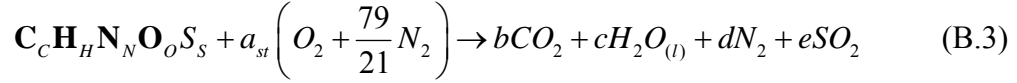
$$\bar{h}_{DB,in} = \bar{h}_{f,DB}^0 + w \left(\bar{h}_{f,H_2O(l)}^0 + \bar{c}_{p,H_2O(l)} (T_{in} - 298) \right) + m_{ash} c_{ash} (T_{in} - 298) \quad (B.1)$$

Here, the combustible component of the total enthalpy is $\bar{h}_{f,DB}^0$. To express it in terms of the HHV and the molecular weight, MW , one has to begin from the definition of the HHV. The dry, ash free higher heating value, $HHV_{DB,DAF}$ is the theoretical amount of heat that can be released from the combustible material such that both the reactants and the resulting products are at ambient temperature and the water in the products is in the liquid phase. That is, the combustibles undergo a combustion process where all the heat generated is captured or used in a process and not heat escapes with the exhaust products.

$$HHV_{DB,DAF} MW_{DB} = \sum_{in,298} N_k \bar{h}_k - \sum_{out,298,H_2O(l)} N_k \bar{h}_k \quad (B.2)$$

Since both the reactants and the products are assumed to be at 298 K (ambient temperature), the changes in thermal enthalpy are all zero. Furthermore, recall that the enthalpies of formation for O_2 and N_2 are also zero. Consequently, O_2 and N_2 will have no effect on the enthalpy. Also, since DB has relatively little S compared to C and H, one can ignore SO_2 in the products when calculating the total enthalpy.

A stoichiometric kmole balance equation can be used to find the number of kmoles of CO₂ and H₂O in terms of the combustible contents.



Carbon:

$$b = C \quad (\text{B.4})$$

Hydrogen:

$$c = \frac{H}{2} \quad (\text{B.5})$$

Sulfur:

$$e = S \quad (\text{B.6})$$

Substituting into equation (B.2):

$$HHV_{DB,DAF} MW_{DB} = \bar{h}_{f,DB}^0 - C \bar{h}_{f,CO_2}^0 - \frac{H}{2} \bar{h}_{f,H_2O(l)}^0 - S \bar{h}_{f,SO_2}^0. \quad (\text{B.7})$$

Solving for $\bar{h}_{f,DB}^0$ and plugging into equation (B.1):

$$\begin{aligned} \bar{h}_{DB,in} = & HHV_{DB,DAF} MW_{DB} + C \bar{h}_{f,CO_2}^0 + \frac{H}{2} \bar{h}_{f,H_2O(l)}^0 + S \bar{h}_{f,SO_2}^0 \\ & + w \left(\bar{h}_{f,H_2O(l)}^0 + \bar{c}_{p,H_2O(l)} (T_{in} - 298) \right) + m_{ash} c_{ash} (T_{in} - 298). \end{aligned} \quad (\text{B.8})$$

In the present work, the DB fuel will not be heated before the combustion process, therefore T_{in} will be 298K, and hence (B.8) reduces to

$$\bar{h}_{DB,in} = HHV_{DB,DAF} MW_{DB} + C \bar{h}_{f,CO_2}^0 + \left(\frac{H}{2} + w \right) \bar{h}_{f,H_2O(l)}^0 + S \bar{h}_{f,SO_2}^0. \quad (\text{B.9})$$

From (IV.12), we can equivalently write the total enthalpy as in equation (IV.18). However, if the DB is preheated, then one should use (B.8) with T_{in} being the preheat temperature.

APPENDIX C

VAPOR POWER CYCLE EFFICIENCY

A typical vapor power cycle is shown in Fig. C.1.

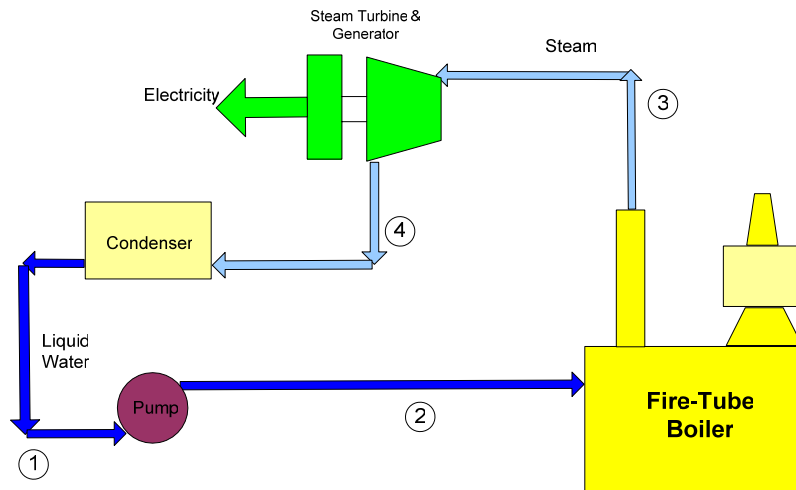


Fig. C.1. Vapor power cycle.

The cycle is usually designed between two pressures: the boiler pressure, $P_2=P_3$ and the condenser pressure, $P_4=P_1$. The mass flow rate of the water, \dot{m}_w , the temperature at the turbine inlet, T_3 , and the condenser exit, T_1 , are also typically design variables. The process can be graphically represented by a temperature-entropy diagram. See Fig. C.2. The state of the water can be found at any point given any two properties of the water, except in the two-phase region (blue dome in Fig. C.2) where the quality, x , must be computed before fixing the state. In Fig. C.2, state 4 is still located in the superheated vapor region; however, this is not necessarily the case. In real systems, the quality at state 4, should be at least 90-95% to prevent damaging the turbine.

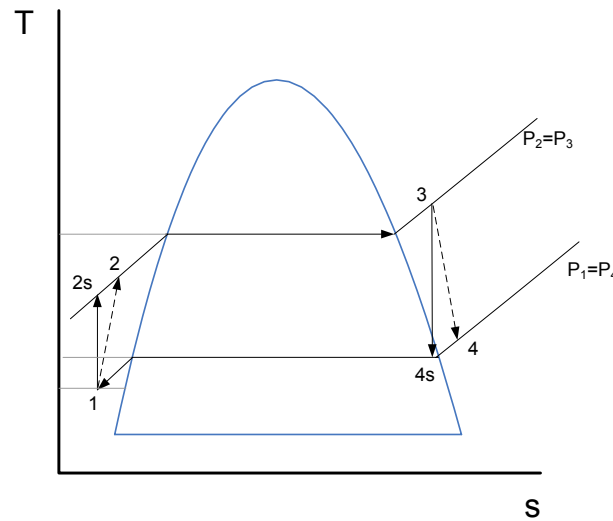


Fig. C.2. T-s diagram for vapor power cycle.

Furthermore, the isentropic pump and turbine efficiencies are η_p and η_t .

Pump:

We can begin with a first law analysis of the pump. Since T_1 and P_1 are known, one can use steam tables to find the specific volume, v_1 , and the specific enthalpy h_1 .

The reversible pump work is:

$$\left(\frac{\dot{W}_p}{\dot{m}_w} \right)_s = v_1 (p_2 - p_1). \quad (\text{C.1})$$

The isentropic enthalpy at state 2 can be computed as:

$$h_{2s} = \left(\frac{W_p}{m_w} \right)_s + h_1. \quad (\text{C.2})$$

Then accounting for the inefficiencies in the pump one can calculate the actual enthalpy and thus, the state, at 2:

$$h_2 = \frac{h_{2s} - h_1}{\eta_p} + h_1. \quad (\text{C.3})$$

Boiler:

Next, since P_3 and T_3 are known, h_3 can also be found. Thus the required heat transfer into the boiler can be computed as:

$$\frac{\dot{Q}_w}{\dot{m}_w} = h_3 - h_2 \quad (\text{C.4})$$

This heat transfer must be comparable to the heat generated by the combustion process discussed in Chapter IV.

Turbine:

The first step in analyzing the turbine is determine if state 4 is in the two phase region or in the superheated region. To do so, notice that the isentropic state 4, $4s$, will have the same entropy value, s , as state 3. If state $4s$ is in the superheated region, then the state is fixed because entropy and pressure, P_4 , are both known. However, if state $4s$ is in the two-phase region, then the quality must be found.

$$x_{4s} = \frac{s_3 - s_{4f}}{s_{4g} - s_{4f}} \quad (\text{C.5})$$

Where s_{4f} and s_{4g} are the entropies at saturated liquid and saturated vapor, respectively.

Finally with state $4s$ fixed we can find the enthalpy.

$$h_{4s} = x_{4s} (h_{4g} - h_{4f}) + h_{4f} \quad (\text{C.6})$$

Then taking into account the efficiency of the turbine, find the actually state 4.

$$h_4 = h_3 - \eta_t (h_3 - h_{4s}) \quad (\text{C.7})$$

The actual quality at state four is:

$$x_4 = \frac{h_4 - h_{4f}}{h_{4g} - h_{4f}}. \quad (\text{C.8})$$

And subsequently, the turbine work is:

$$\frac{\dot{W}_t}{\dot{m}_w} = h_3 - h_4. \quad (\text{C.9})$$

Condenser:

The heat transfer rate to the condenser water is:

$$\frac{\dot{Q}_c}{\dot{m}_w} = h_4 - h_1. \quad (\text{C.10})$$

Lastly the cycle's thermal efficiency can be computed as:

$$\eta_{thermal} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_w}. \quad (\text{C.11})$$

VITA

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