Recovery of energy from wastewater and solid wastes by anaerobic treatment

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Abstract

Many wastes have high levels of energy content which could be recovered effectively by biological means. Under anaerobic conditions, bacteria convert wastes into methane-rich biogas which could then be used as fuel. Livestock wastes and sludge from wastewater treatment plants have been treated by this means for many years. However, the recent rapid development of anaerobic technology has extended its applications to many other areas, including anaerobic treatment of various wastewaters, strategic biogas collection of sanitary landfills, and production of bio-energy for rural farms in underdeveloped countries. Details of these applications are discussed.

Introduction

It has often been overlooked that most of the wastes, either solid or in wastewater, have substantial amount of energy content which, in many cases, could be recovered effectively under properly designed conditions. With careful planning and proper designs for recovering the residual energy, the cost of waste disposal could be significantly reduced in most cases, while in some cases waste disposal could even produce profit.

Incineration is the most common means to recover the residual energy content in concentrated wastes. In rural areas of developing countries, peasants often burn the dried manure of cattle and horses for heating and cooking. In many large municipalities of developed countries, on the other hand, sophisticated incinerators are installed for the disposal of solid wastes and the dewatered sludge from the wastewater treatment plants. Part of the energy content in the wastes and the sludge are recovered from the high temperature exhaust gas by generating steam for electricity. Nevertheless, large scale incineration systems are very expensive because they require sophisticated equipment and the materials of construction for the high temperature process. Furthermore, they also require the installation of electrostatic precipitators and other pollution control devices for the removal of pollutants from the exhaust air.

Anaerobic treatment is an alternative to incineration for recovery of energy from concentrated wastes. However, it has a broader application than incineration because it could also recover energy from the not-so-concentrated wastes, such as wastewaters. This process relies on bacteria in nature to decompose organic compounds in the absence of oxygen (Ref 1). It does not require expensive equipment and is very effective when the process is operated properly. Moreover, the gas product of the bio-degradation process contains high levels of methane, a highly flammable gas which could produce energy upon combustion.

The anaerobic process for many years has been used for the disposal of solid wastes and slurries containing high levels of organics, such as livestock wastes (Ref 2 & 3) and sludge from wastewater treatment plants (Ref 4). Energy content of the wastes could be effectively recovered in large scale operations.

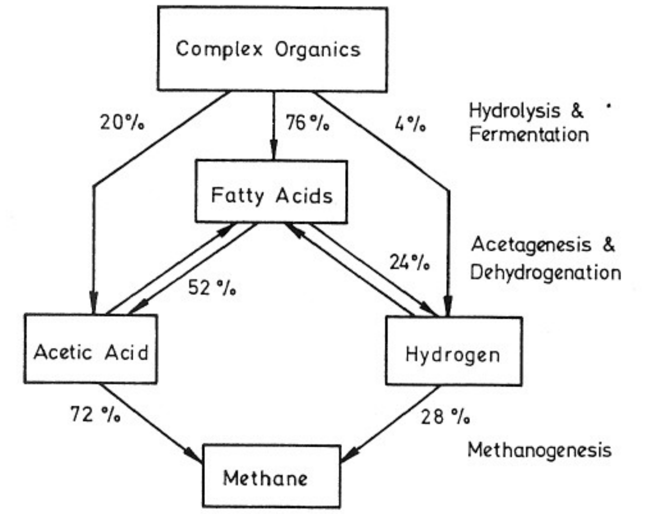

Figure 1: Organic Pathways of Anaerobic Conversion

Solid wastes in a sanitary landfill, under the natural anaerobic conditions, are bio-degraded into methane and carbon dioxide. The biogas with high fuel value could be collected from a landfill site for over 10-20 years (Ref 5 & 6). Dair (Ref 7) estimated that if all the gas in the landfills in the United States were collected, 2% of the national demand of energy could be satisfied. It has now become practical to harvest the biogas produced at the large scale sanitary landfills to generate electricity for the community (Ref 8).

The rapid development of anaerobic technology in the past decade has made the anaerobic process a viable means for the treatment of many industrial wastewaters (Ref 1 & 9). More recently, successful applications to the treatment of low strength municipal wastewater have also been reported (Ref 10 & 11). It should be noted that wastewaters are traditionally treated aerobically. The merits of anaerobic treatment of wastewater rely not only on the amount of energy it could produce, but also on the energy it saves from the alternative aerobic treatment processes.

Over 5 million household anaerobic digesters have been in operation in rural China (Ref 12). Wastes, such as animal and human excreta, straws and stalks, etc., are bio-degraded in digesters, producing methane-rich gas which likely is the only energy supply available for many peasants who use this energy for cooking, heating and many other farm uses.

This article is to review in detail about these applications of anaerobic treatment for the recovery of energy from various wastes and wastewaters.

Principle of anaerobic degradation

In nature, microorganisms degrade complex organic matters into simple molecules, obtaining energy through this process for their growth, locomotion and reproduction. Biological degradation processes may be roughly classified as either aerobic or anaerobic, depending on the oxygen requirement. In the former process, organic matters are degraded in the presence of oxygen into carbon dioxide; whereas in the latter, organic matters are degraded in the absence of oxygen into mostly methane and some carbon dioxide.

Wastes degrade anaerobically in nature. For example, dead plants and algae at the benthos of shallow water bio-degraded in the absence of oxygen, producing "swamp gas". Man also has disposed of human and animal excreta by using cesspools, where wastes degrade anaerobically; residue discharges from the cesspool containing high levels of nutrients are often used to fertilize the farmland.

Anaerobic degradation of organic matters involves a complex interaction of three groups of microorganisms, as illustrated in Fig 1 (Ref 13). The first group is the fermentative bacteria, which hydrolyzes complex molecules, such as proteins and cellulose, into fatty acids, alcohols and other soluble organics. The second group, acetogenic bacteria, converts fatty acids into acetic acid, which is further degraded by the third group, methanogens, into the end-products, i.e. methane and carbon dioxide.

Among the three stages of anaerobic degradation, the rate is often limited by the hydrolysis step, indicating that it is relatively more difficult for microorganisms to break down complex molecules into simple ones. Temperature is one of the most important parameters which affect the overall degradation rate. Mesophilic bacteria at their optimal temperature range of 35-38°C have a much higher degradation rate than the bacteria at the ambient temperature. Another important parameter is pH. Because methanogens are sensitive to pH, anaerobic processes are normally kept within the range of pH 6-9. Acidity could be built up if the fatty acids produced by the acetogenic bacteria could not be effectively consumed by the methanogens. In this case, methane production would cease and the products of the anaerobic degradation would be mainly composed of fatty acids.

By nature, the anaerobic degradation is conducted under very reductive conditions. Elements are thus converted to their respective reductive forms during anaerobic degradation. Sulfur and nitrogen in the wastes are converted to hydrogen sulfide and ammonia, respectively. The biogas generated from the anaerobic degradation is generally composed of 50-70% methane, 30-45% carbon dioxide, and some hydrogen, plus hydrogen sulfide and ammonia. The biogas has to be handled with care, because hydrogen sulfide and ammonia are obnoxious in odor, while methane is explosive when exposed to air. On the other hand, the biogas has very high fuel value (about 22,000 kJ/m^3) and could be effectively recovered to produce energy.

Energy recovery from sludge of wastewater treatment

In a typical municipal wastewater treatment plant, wastewater first flows through bar screens and the grit removing chamber for the preliminary treatment. It is followed by the primary treatment in which suspended solids are precipitated in a settler and removed as so-called primary sludge; about 30% of the Chemical Oxygen Demand (COD) of the wastewater is removed as the primary sludge. After primary settling, the wastewater is then treated aerobically in the secondary treatment, which would remove 80-95% of remaining COD, followed by another settling process. The supernatant of the second settler is discharged to the receiving water, whereas the settled so-called secondary sludge has to be disposed of, often along with the primary sludge.

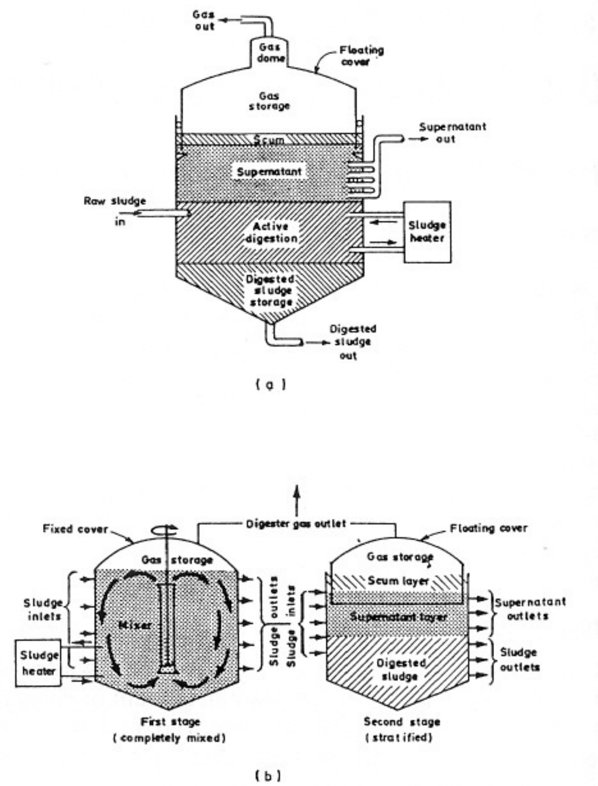

Figure 2: Anaerobic Sludge Digesters, (a) Standard, and (b) Two-Stage High Rate

Large anaerobic tanks are commonly used to digest both the primary and the secondary sludges. The aims of the sludge digestion process are threefold: to kill the pathogens, to reduce the sludge volume thus the cost of sludge handling and disposal at the downstream, and to produce biogas which can be effectively recovered.

Fig 2 shows two types of anaerobic sludge digesters, i.e. standard and two-stage high rate digesters (Ref 4). Standard digesters usually do not provide mixing, resulting stratification and thus poor contact between the sludge and the anaerobic microorganisms in the digester. However, it has a simple design and requires little maintenance. High rate digesters, on the other hand, require some forms of mixing, either by mechanical agitation or by recirculating the gas produced. Because heat could be readily provided by burning the biogas, both types of digesters are commonly operated at about 37°C, the optimal temperature for the mesophilic bacteria. The hydraulic retention time (HRT) is normally maintained at 20-30 days, although some digesters keep the HRT as high as over 60 days. The sludge loading rates are 0.5-1.1 kg/m^3-day and 1.6-6.4 kg/m^3-day, respectively, for standard and high-rate digesters.

The biogas produced from the sludge digesters is composed of 65-70% methane. The digesters on the average produce biogas at a rate of 23 L/person-day in primary municipal treatment plants, or 28 L/person-day in secondary treatment plants. Energy produced from the biogas could be used for the treatment plant operations, including heating the digester, drying the dewatered sludge for final disposal, pumping wastewater and sludge, and running compressors for aeration.

In the Shatin Wastewater Treatment Works, biogas from the digesters provides about 40-50% of the total energy required for the wastewater pumping stations and for aeration in the secondary treatment process.

Energy recovery from livestock wastes

Waste digesters for the livestock farms are usually built using the standard type design for low cost and simple operation. They are mostly operated at a loading rate of 1.6-4.8 kg wastes/m^3-day with a retention time of 10-20 days. The wet digested residue retains most nutrients and could be used as fertilizer. Jewell and Loehr (1977) reported the daily biogas production rates for different livestock based on body weights are:2.55, 2.46, 2.69 and 6.91 L/kg for dairy cattle, beef cattle, swine and poultry, respectively. The biogas contains about 60% methane. It was estimated that the anaerobic digesters for a 100-cow dairy farm would produce 154-217 m^3 biogas daily, depending on the treatment system.

Some of these livestock wastes digesters are quite large. Meckert (Ref 3) reported that two 3,800 m^3 anaerobic digesters were installed in the late 1970's to handle 360,000 kg/day of dry matter (equivalent to manure from 110,000 cattle) and produced 45,300 m^3/day of methane. Meyer and Guthrie (Ref 14) on the other hand reported the installation of a 11,000 m^3 anaerobic digestor using a more advanced plug-flow design. Biogas produced from these digesters is used for heating and electricity generation for farm uses.

Energy recovery from wastewater and energy saved from aerobic treatments

Anaerobic process has been misconceived to be slower and more susceptible to change of process conditions than the aerobic process. As a result, its application was limited, until the 1980's, mostly to the digestion of treatment plant sludge and livestock wastes. However, the anaerobic technology has advanced rapidly in the last decade, resulting from a better understanding of the bacterial need of trace elements and response to toxicants, and, most importantly, the sophisticated designs of the new reactors.

It is comprehended only recently that iron, cobalt, nickel, and sulfide are obligatory nutrient requirements for methanogenic bacteria to convert acetate to methane. Trace metals, such as molybdenum, tungsten and selenium, have also been reported to be required for the anaerobic process.

The susceptibility of methanogenic bacteria to chemicals has led to a commonly held belief that anaerobic process is not appropriate for treatment of most industrial wastewaters. However, it has been found that anaerobic bacteria can tolerate a wide variety of toxicants and even bio-degrade some of them (Ref 9). For instance, two full-scale treatment plants are operated on paper bleaching mill to bio-degrade toxic chlorophenols. In addition, acclimation to toxicity and reversibility to toxicity are commonly noted. It was reported that methanogens can fully recovered within 24-48 hours, after being exposed to toxicants for 1-24 hours at concentration of toxicity 100 times required to stop methane production.

However, the most important development on the advancement of the anaerobic technology is the improvement of anaerobic reactor designs, many of which were adopted from technologies previously developed by the chemical industry. Fig 3 illustrates some of these new designs, including upflow anaerobic filter, downflow packed bed, fluidized bed and upflow anaerobic sludge blanket reactors. These designs allow a high concentration of anaerobic bacteria and an intimate contact between the pollutants and the bacteria in the reactors. (Ref 1)

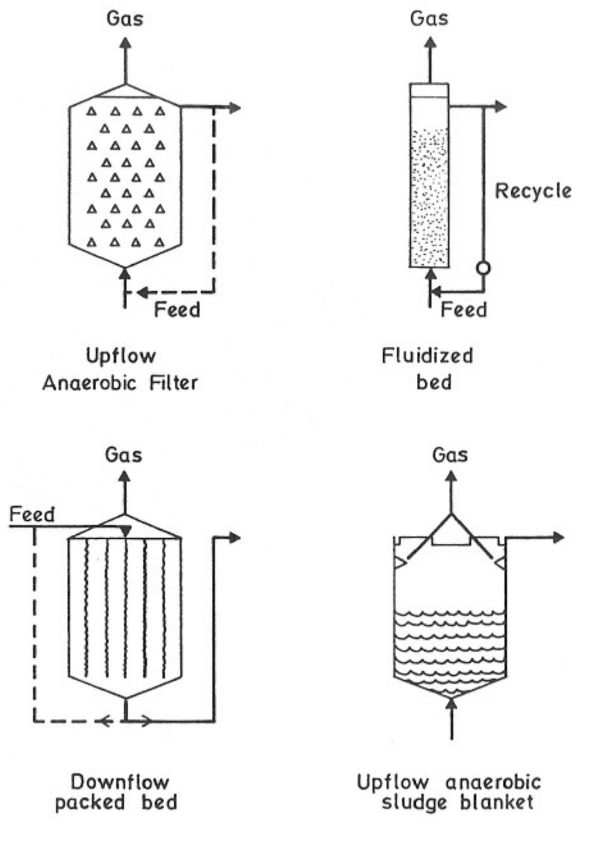

Figure 3: Recent Designs of Anaerobic Reactors

All of these recent advancement on the anaerobic technology have resulted in the wide applications of anaerobic treatment to many high-strength industrial wastewaters in the last 10 years (Ref 1, 15, 16). As compared to the more popular aerobic processes, anaerobic processes have several advantages. First, its sludge production is only about 10% or less of that of a typical aerobic process. It thus saves large sum of capital investment for the sludge handling and disposal, which is about 40-50% of the capital cost for an aerobic treatment plant. Secondly, anaerobic process produces methane-rich biogas which could be recovered for energy. Fang, et al (Ref 15) reported each kg of COD removed would produce 0.45 m^3 of biogas. Thirdly, it saves the tremendous amounts of energy which would otherwise be required by its alternative, the aerobic process. Aeration is the most energy intensive operations in the wastewater treatment system, responsible for 50-90% of the total energy cost of a typical municipal wastewater treatment plant (Ref 17). A 1982 survey on the North America Continent showed that 1.3 million kilowatts of aeration equipment (costing about US$600-800 million) were installed for wastewater treatment, at an operating cost of US$600 million a year. Speece (Ref 9) estimated that the net energy savings between anaerobic and aerobic treatment could be as high as US$250 per metric ton of COD.

It is interesting to note that, more recently, the anaerobic treat-

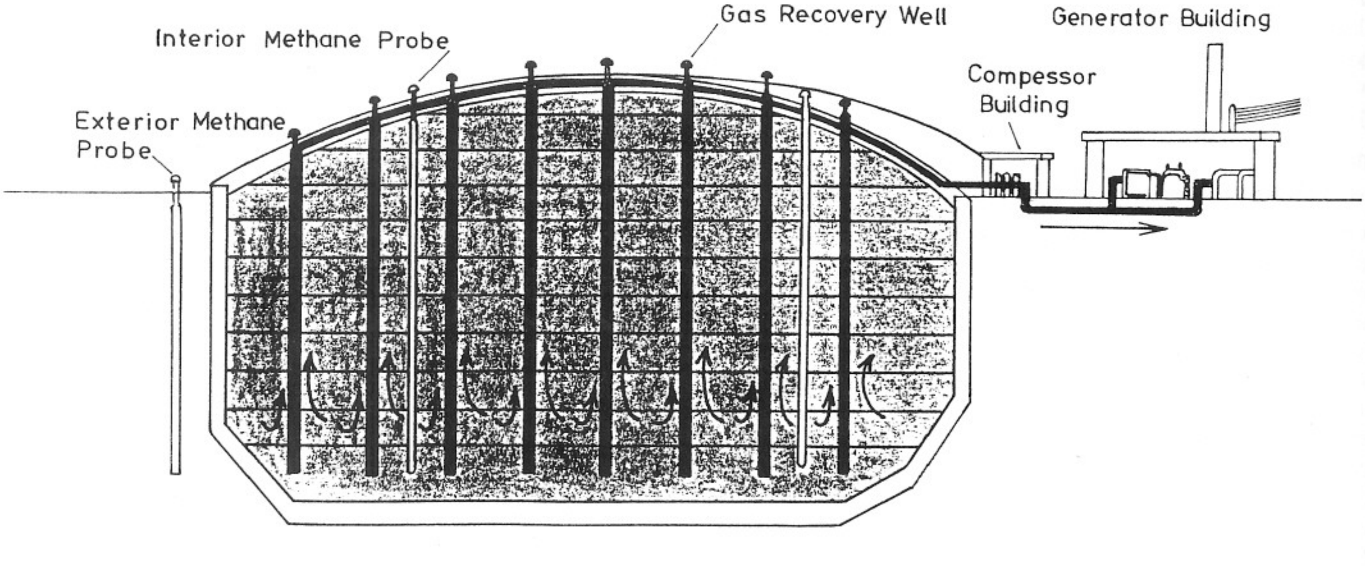

Figure 4: Collection of Landfill Gas for Energy Generation

ment has even applied to low strength wastewater (Ref 11) and municipal wastewater for communities as large as population of 200,000 (Ref 10).

Energy recovery at rural farms in developing countries

In rural China where often electricity supply is unavailable or in short supply, anaerobic digestion of domestic and animal wastes plus other farm wastes, such as straw, stalk, etc., produces energy for cooking, lighting and heating for many peasant families. As of 1988, about 5 million digesters, most are of the size of 6-8 m^3, have been built producing 1 trillion m^3 biogas per year (Ref 18). The largest single digester has the size of 8,000 m^3 (Ref 12).

The Ministry of Agriculture, Animal Husbandry and Fishery in China even established a Biogas Research Institute in Chengdu, Sichuan, to study and to promote the applications of this form of energy production in rural China. Their development efforts are focused on building small, simple, but efficient digesters at low cost for single household, and building large digesters for wastes from communes and wastewaters from industries in order to produce biogas as part of the gas supply to the community.

Energy recovery from sanitary landfills

Sanitary landfill is a common means for solid wastes disposal. To avoid contaminating the groundwater by the leachate, new landfills are commonly designed to line the basin with impermeable clay or synthetic liners. Leachate collected at the bottom are treated before they are discharged to the receiving water. The top surface of the landfill site is also covered with soil or clay. The landfill basin is like a reactor, inside which solid wastes undergo anaerobic degradation in the absence of oxygen. Biogas is produced after the initial stage of acclimation and water accumulation. The gas production rate depends on a number of parameters, including the density, compositions and moisture contents of the wastes, as well as the age of the landfill.

Like in other anaerobic processes, the landfill gas is composed of methane, carbon dioxide, ammonia, hydrogen sulfide, etc. The gas is highly flammable. It may seep underground over distances up to 300 metres into nearby buildings, where at the concentration level of 5-15% in air it can explode upon ignition. Over twenty such cases occurred in the United States, resulting in 5 deaths (Ref 8). The biogas also reduces oxygen in soil and thus may kill vegetation near the landfill.

Therefore, gas collection systems are now installed in about 100 or more landfills in the United States to collect the landfill gas. It not only reduces the danger of landfill gas leakage to the surrounding environment, but it also could produce energy. Large blowers or vacuum pumps are installed to withdraw gas from a series of wells in the landfill, as shown in Fig 4. Close monitoring of oxygen is required to ensure minimum amounts of air seeping into the landfill. Leaked air would suppress the anaerobic bio-degradation process, lower the fuel value of the collected landfill gas, and furthermore cause fire.

It has been estimated (Ref 5, 6) that a typical landfill could produce biogas for power generation for over 10-20 years. According to another estimate (Ref 7), 2% of the US energy demand could be satisfied if all biogas from landfills were collected. In the US, landfill gas has been collected and used directly as fuel for industrial boilers, or used to generate electricity, or, in some cases, upgraded to pipeline quality for delivery to utility distribution system. Some landfill collection system has generated electricity for over 10,000 homes (Ref 5, 8).

Conclusion

Proper disposal of municipal, industrial and agricultural wastes and wastewaters is undoubtedly necessary for the protection of our environment and the balance of ecology. Many feel that the proper disposal of wastes is expensive, but they often overlook that there are significant amounts of residual energy in the wastes and wastewaters which could be effectively recovered using anaerobic treatment processes.

Some of the applications, such as sludge and livestock waste digestions, have been in practice for years; however, development is still in progress to improve their efficiencies. New applications, such as wastewater treatment, landfill gas recovery and energy generation for rural areas of developing countries, have progressed rapidly in the last decade. Further development is expected in the coming years.

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