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Engineering of Microbial Garbage Treatment Plants

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The design and operation of composting and/or garbage treatment plant has been carried out mainly based on empirically obtained data in many cases, which caused various troubles such as generation of bad smells and low performance in decomposing organic waste. This study intends to establish a method of design and operation of this kind of plant on the basis of chemical engineering aspects such as material and heat (enthalpy) balance, kinetic analysis of reaction and/or mass transfer rate, and various equilibrium relations. The major operating factors considered here are as follows: the rate of aeration, the control of temperature and moisture content in the reactor, pH, mixing conditions, organic loading to the reactor, and others.

1. Introduction

The total amount of food waste in Japan is about 17.1 million tons (Mt) from the total input (food) of 84.4 Mt, in which 10.7 Mt is discharged from homes and 6.4 Mt is from business activities. This amount corresponds to 22.2% of total non-industrial waste of 48 Mt. About 13 Mt of food waste is incinerated and disposed; only about 4 Mt is recycled (mainly the wastes from business activities), which causes many troubles and difficulties in treating and disposing of refuse. Thus, effective recycling and use of food waste as a biomass resource has a large significance in our society.
Although there are many options for the treatment of garbage (food waste), each option has its own weak point. Among the many possible methods, a microbial decomposition type of garbage treatment system is considered to be one of the most environmentally-friendly options [1]. In the previous study, the author proposed a small-scale static-type garbage treatment system for household use (input: 0.6 to 0.8 kg-garbage per day). The system has a simple structure but shows quite an excellent performance in garbage treatment by microbial decomposition with little generation of bad smell, as well as only a small consumption of electricity [2]. On the other hand, this study focused on large-scale (input: several tons of garbage per day) treatment plants. Since composting plants are one of the biochemical reaction processes, the design and operation should be accomplished in terms of chemical engineering aspects. Thus, the purpose of this study is to establish a methodology of the large-scale garbage treatment plants using the approach of chemical engineering.

2. Understanding the problems

The basic principle of the operation of garbage treatment plant is similar to that of composting plants, in which aerobic microbes play a key role in the decomposition of garbage. Composting plants of organic wastes such as cattle manure have a long history [1], but the operating conditions have been determined on an empirical basis. This situation has been long continued and there has been little progress so far into the methodology of the design or the determining the operating condition of garbage treatment plants [3]. Recently in Japan, large scale garbage treatment plants have often suffered from various troubles, mainly generation of bad smell. This is probably because the design and operation of the plants has been carried out mainly based on empirically obtained data in many cases. The essential reason of this situation would be that the microbial garbage treatment system is a "complex system", in which many factors interact in diverse ways. For instance, temperatures as well as moisture content in the reactor are both very important factors dominating the microbial activity, and act as a cause while at the same time as a result of microbial decomposition process. For example, if temperatures rise, activity of microorganisms generally accelerate causing a greater heat generation by aerobic decomposition of garbage, which in turn pushes the temperature up and evaporation of water in the garbage increases, affecting the moisture content in the reactor, which brings about a positive or negative effect on the activity of microorganisms. Other factors act in a similar manner. The considerations of the optimal design and operation of garbage treatment as well as their interrelations are summarized as follows:

Reactor	Operating Factor	Conditions in the Reactor	Treatment Results
shape and size	temperature	temperature	reduction rate (weight and volume)
aeration	moisture content	moisture content	
temp. control	mixing (time, intensity)	density	smell generation
mixing system	organic loading	viscosity	
bulking agent	garbage property	pH	
recycled residue		ORP	
accelerator for microbes		microorganisms	

This situation would be the major reason why the design and operation of the composting and garbage treatment plants has long depended on skills and experiences of operators, which would be a kind of "fuzzy control system" using a high level of human knowledge. However, the operating factors should be determined on an engineering basis, even though the situation is so complicated, in order to achieve a stable operation regardless of the skills of the operators. A methodology for determining the amount of aeration is discussed as the first step in this study.

3. Aeration

There are three major purposes of aeration in the composting and garbage treating process:
a) Removal of the water generated in the garbage decomposition process.
b) Oxygen supply to the oxidation reaction of organic contents in the garbage.
c) Controlling of the temperature in the reactor.

3.1 Airflow required for the removal of water

The amount of airflow required to fulfill the above demands can be estimated using the model calculation as follows: Firstly, the amount of water vaporized should be determined.

Assumption (1) :
Basis of calculation: 1 kg of a model garbage sample, moisture content = 80%, decomposition rate of the organic contents (dry basis) = 70 %, moisture content of the product = 40%, the elemental composition of the dry organic contents: $C_{24}H_{40}O_{10}$ (based on an actual sample analysis).
In this case, the complete oxidation of the organics results in 1056(=24×44) grams of CO_2 and 360(=40/2×18) grams of H_2O (metabolic water) from 488 grams of dry organics.

	Before	After
Moisture	800 g	60(1 - 0.4)/(1 - 0.6) = 40 g
Dry Matter	200 g	200(1 - 0.7) = 60 g

thus, Decomposition of Dry Matter = 200 - 60 = 140 g
The amount of water evaporation = 760(= 800 - 40) + 140 × 360/488 = 863 g/ kg-wet garbage.

Assumption (2):
Input air condition: saturated humidity of air at 20 ℃ = 0.0147 kg-water/kg-dry air (d.a.), if relative humidity = 40%, absolute humidity of air at the input = (0.0147)(0.4) = 0.00588 kg-w/kg-d.a. Output air condition: saturated humidity of air at 60 ℃ = 0.1522 kg-w/kg-d.a., if the output air is saturated with water vapor, the absolute humidity of the air at the output = 0.1522 kg-w/kg-d.a., then the amount of air required for the removal of the vaporized water V can be estimated as follows:

863 g-water = V m^3-d.a. × 1.29 kg-d.a./m^3-d.a. × (152.2 - 5.88) g-water/kg-d.a.

thus, V = 863/(1.29)(146.32) = 4.57 m^3.
This is the minimum required amount of air to remove water. If the garbage input is once a day, the decomposition process should take one day, then, the air flow rate = 4.57 m^3/1 day/kg-wet garbage = 190 L-air/hr/kg-wet garbage. If organic loading to the reactor is 40 kg-wet garbage/m^3-reactor, the air flow should be (190)(40)/(60) = 127 L-air /min./m^3-reactor. This value is generally consistent with the value shown in a design manual of livestock manure composting facilities [4], more than 100 L-air /min./m^3-reactor when the height of compost heap is higher than 1 m.
The absolute humidity of air H is a function of total air pressure P and partial pressure of water vapor p as follows:

$$H = (18/29) \times p/(P - p) \quad (1)$$

$$p = \psi \times p_s \quad (2)$$

where ψ is relative humidity [-], and p_s is the partial pressure of water saturated vapor. The

$$\log p_s = 7.06 + 1650/\{46.8 - (273.15 + t)\} \quad (3) \quad \text{Antoine Equation}$$

where t is the temperature of water vapor [℃].
Thus, the value of H is a function of ψ and t if the total pressure of air P is constant, meaning that air flow required for the removal of water varies with the conditions of input/output air, and the input condition depends on season and weather.

3.2 Airflow required for the supply of oxygen

The amount of air flow required for the supply of oxygen can be calculated from the oxygen demand as follows: from the elemental composition of dry organic contents assumed, the oxygen necessary for complete oxidation of organic compounds should be 24(for 24 C) + 10 (for 40/2 H_2) = 34 mol-O_2 per 488 grams of dry organics. Since the decomposition rate of organic contents (dry basis) was assumed to be 70%, the net O_2 demand is (34)(0.7) = 23.8 mol-O_2, corresponding to 23.8/0.21 mol-d.a. × 22.4 L/mol-d.a. × 1/1000 m^3/L = 2.54 m^3.
Thus, the air required for oxygen supply is about half of the minimum amount required for water vapor removal (4.57 m^3). Generally, the demand of air for oxygen supply is smaller than that of water vapor removal, suggesting that the oxygen demand can be automatically fulfilled if the amount of air flow is larger than that required to remove water. Note, however, that whether or not air is uniformly distributed in the reactor is another problem, which is very important to maintain aerobic condition in the reactor. If air is not distributed uniformly, e.g. a bypass of airflow is formed, then anaerobic portion occurs even if the amount of air itself is sufficient, which is a main cause of the generation of bad smells. In such a situation, mixing operations play an important role.

3.3 Airflow required for controlling temperature

The amount of air flow required for the temperature control can be estimated by calculation of heat balance as follows:
Assumption (3):
Low combustion heat of dry matter = 4200 kcal/kg-dry, then the heat generation by the oxidation of decomposed dry matter 140 g is (4200 × 0.140 =) 588 kcal. The heat of evaporation of water 863 g is (540 kcal/kg-water × 0.863 =) 466 kcal, which is 79% of the heat generation, meaning that the major part of the heat generated by the decomposition of garbage would be consumed by the

evaporation of water. If a steady state is maintained, the rest of the heat generated would be utilized by the rise in the temperature in both phases of solid (garbage residue) and gas (air and water vapor) and heat loss. If the temperature difference is 40 degrees (output 60 ℃- input 20 ℃), and the heat capacity of dry air between 0 to 70 ℃ is assumed to be 0.24 kcal/(kg・K), the heat needed for rising temperature of 4.57 m^3 air is 4.57 m^3 × 1.29 kg/m^3× 0.24 kcal/(kg・K) × 40 K = 56.6 kcal, which is about half of the rest heat (588 - 466 =122 kcal). This sensible heat is about 1/10 of heat generation (588 kcal), meaning that a very large amount of air would be required if there happens to be a need to cool the garbage decomposition process only by aeration since the heat capacity of air is very small.

4. Controlling of moisture content

The moisture content in the garbage treating system is one of the most important operating factors, which affects both aeration efficiency and activity of microorganisms. In the case of a high moisture content of 70% or more in the system, the aeration efficiency would tend to reduce and result in an increase of anaerobic portion in the reactor, which in turn would derive a bad smell. The activity of microorganisms is almost constant between 40 to 60% of moisture content, optimum range; thus the moisture content should be controlled within this range by aeration and moisture adjustment of the input substrate (garbage and material for microbial beds). Since there seems to be no suitable remote sensing of moisture in the reactor with high accuracy and reliability so far, the development of a good moisture monitor without sampling or touching would have a great significance.

5. Other factors

The other major important factors for operation were mixing, organic loading, pH, and others.

5.1Mixing

The purpose of mixing is to maintain a homogeneous condition in the reactor as well as to improve an efficiency of aeration, and to prevent the reactor from falling into anaerobic conditions. But, too intense mixing would bring about harmful effect on the garbage decomposition process by excess loss of heat and moisture in the reactor. Thus, the frequency and intensity of mixing is an important consideration, but is very difficult to discuss on a basis of engineering, because mixing operation of solid mixture is much more complicated than that of continuous fluid, for which equation of continuity and Navier-Stokes equations can be applied. Also, the density as well as viscosity of the solid mixture would be changed according to moisture content, temperature and the condition of microbial ecosystem in the reactor. Since there are so many agitation methods of solid mixture, it is an important technological problem to select the most suitable mixing system although there is no established method to estimate an effectiveness of mixing quantitatively.

5.2 Organic loading

An organic loading to the reactor is defined as an amount of garbage input per unit volume of the reactor per unit time (usually one day). This operating parameter is also very important for the stable operation of the plants. According to the results in the authors' lab, a moderate organic loading would be around 40 to 50 kg-wet garbage/day/m^3-reactor. If the amount of garbage input is too large, several undesirable symptoms occur, such as low performance of garbage decomposition, the creation of bad smells, drops in pH and temperature, and decreases of the total number of microbes, which is called a state of "overloading". Although the overloading phenomenon is generally observed in many organic waste-treating processes using microorganisms such as activated sludge and methane fermentation, a detailed mechanism of overloading has not yet been clarified because this phenomenon seems to have a large degree of complication. The analysis of the overloading phenomenon in garbage decomposition is currently in progress in the authors' lab.

5.3 pH and others

Since the appropriate range of pH for the growth of most microorganisms is around 6 to 8, pH in the reactor should be maintained in this range. However, the value of pH is a result of microbial activities with many kinds of biochemical reactions. For instance, the decomposition of nitrogen containing substances such as protein and amino acids generates ammonia, which leads to pH increase, whereas the decomposition of carbohydrate substances accelerates the production of organic acids such as acetic acid and lactic acid, which brings about pH decrease. Thus, the control of pH is not an easy task. Forced adjustment of pH using chemicals, acids and alkalis, is not always an effective way to maintain the stable condition in the reactor, and no adjustment would be better since the pH value would reach the appropriate range naturally if the decomposition process exceeds in a normal way. Thus the adjustment of aeration or mixing to maintain the suitable range of temperature and moisture content in the reactor is more significant.
There are still many factors to be considered. For example, ORP in the reactor, bulking agent (rice husks or fine woodchips), garbage property, the use of recycled residue and its properties, accelerators for microbes, and so on. However, it is difficult to discuss them on the basis of engineering as of yet.

6. Conclusion

The major parameters for design and operation of large-scale microbial garbage-treating plants should be determined not by empirical basis but by the engineered approach shown in this study. However, the approach shown here was only an elementary stage of the operation design. In the next step, a simulation model will be developed in which the material balance of water/oxygen, heat balance, and the terms of bacterial activity will be included.

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