Design and Performance of Helical Ribbon and Screw Impeller Aerobic Compost Bioreactor

Zheng Yang, Hong Miao, Xunyi Ge, Xuehao Chen, and Ruihong Zhang

***Abstract*—In order to solve problems of raw materials present in the compost reactor are compacted blocks, poor ventilation performance, large ventilation resistance, and difficulty in homogenizing the product, a helical ribbon and screw impeller aerobic compost bioreactor was developed. Through numerical simulation of the flow field, it is proved that the helical ribbon and screw impeller has a good agitation and axial flow property. The results of the composting test show that the time above 55 ℃ for the top, middle, and bottom layers is 5.2, 4.7, and 4.3 days. During the reaction, the oxygen concentration was over 8%, and the final seed germination index of each layer was over 88%, which proved that the experimental reactor can achieve homogenization and can be effectively harmless compost.**

***Index Terms*—Aerobic compost, bioreactor, helical ribbon and screw impeller, CFD.**

I. Introduction

In recent years, with the rapid development of China's livestock and poultry production, it has caused tremendous challenges to the ecological environment. According to statistics, the output of livestock manure in China is about 3.8 billion tons, ranking the first in the country's major pollution emission areas. [1] The use of aerobic compost can realize the reduction, recycling and harmless disposal of these organic solid wastes. [2] It can be divided into static composting, trough composting, barium composting, and reactor composting. Among which the reactor composting method has a short compost cycle, a small floor space, and a good working environment. [3] It has become the current research hotspot and have a good application prospect. [4], [5]

At present, the development of vertical compost reactors is relatively mature. The aerobic composting reaction is a complex transfer process of 'mass-heat-momentum'. [6] The basic research on the reaction mechanism of composting is not yet thorough. At the same time, the compost reactor can be used at present. Experimental devices for the simulation of compost reactions in the laboratory, such as the laboratory compost reactors developed by Han Lujia, Zhang Anqi et al [7]., a tubular compost reactor developed by Guillermo Vidriales-Escobar et al. [8] These vertical reactors are simple in structure, effectively reducing the compost reaction time and improving the composting reaction environment. However, due to the gravity accumulation of materials, there are disadvantages in that the raw materials are compacted, the ventilation performance is poor, the ventilation resistance is large, and the product is difficult to homogenize.

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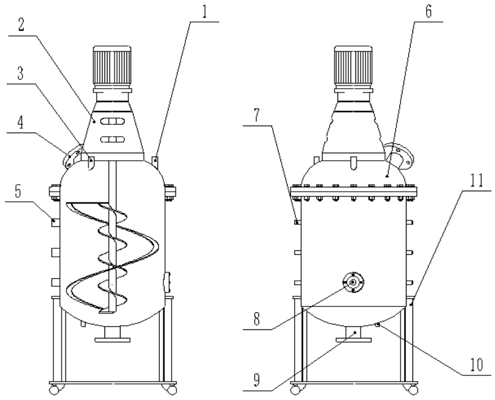
II. Math Design of Aerobic Composting Bioreactor

According to the characteristics of the aerobic composting process, an experimental bioreactor was designed. As shown in FIG. 1, it mainly consists of the reactor material compartment, exhaust port, ribbon-and-screw turning device, and sensor channels.



1. Exhaust port 2. Ribbon-screw turning device 3 Make-up port 4. Inlet port 5. Temperature sensor interface 6. Material compartment 7. Oxygen concentration sensor interface 8. Visual observation port 9. Outlet port 10 . Aeration channel 11. Bracket

Fig. 1. The structure aerobic of compost bioreactor.

A. Determination of Reactor Volume and Basic Dimensions

The necessary condition for maintaining the temperature of the compost bioreactor is [9]:

$$Q_{in} > Q_{ow} + Q_{oe} + Q_{os} + Q_{oA} \tag{1}$$

where is the heat generated by the compost materials in KJ; is the heat taken away by evaporation of water in KJ; is the heat taken away by the environmental heat transfer effect in KJ; is the heat required to warm up the bulk material in KJ; is the heat needed to heat the air in KJ.

When the dry matrix in the stock is, according to the thermodynamics of the composting reaction, the ambient temperature is 25 ℃ and the moisture content of the material is 60%. The ratio of the mass to the effective surface area is calculated by referencing the relevant formula in [10], [11] should meet:

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Since the reactor is designed based on theoretical experiments, considering the actual process of composting, the ratio of diameter to height, and the manufacturing cost, the effective volume of the reactor is determined to be 100L. Referring to the high-diameter ratio of the common mixing vessel of common stirred vessels, the inner diameter D is 500mm and the height is 600mm. All of them are made of 304 stainless steel, and a layer of 20mm thick polyurethane insulation material is added on the periphery. Temperature sensors (PT100, Beijing Jiuchunjian Technology Co., Ltd.) and oxygen concentration sensors (FDM700, Beijing Jiuchunjian Technology Co., Ltd.) are used to monitor the temperature of the tank body at the positions of 150mm, 300mm, and 450mm from the bottom.

B. Design of the Helical Ribbon and Screw Impeller System

For the turning operation of bulk materials, the main purpose is to mix, disperse, promote the movement and heat exchange of materials. The viscosity of compost materials is high. During the composting process, due to the inconsistent reaction process of the bulk materials in different parts, there is a difference in the quantity and activity of microorganisms. Therefore, there is an axial temperature difference in the bulk body, which affects the reaction rate and effectiveness

The device adopts a ribbon-screw stirring system. As shown in FIG. 2, the helical direction of the ribbon-screw is opposite, and has a good axial flow effect. According to reference [12], The ratio of the inner diameter of the container to the outer screw diameter is D/D_j=0.95 , According to actual needs, determine the main parameters as shown in the following table:

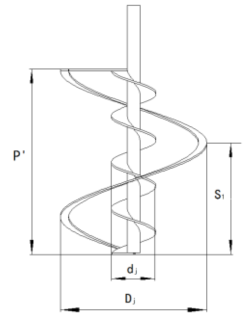


Fig. 2. The helical ribbon and screw impeller.

TABLE I: STRUCTURE PARAMETERS OF HELICAL RIBBON AND SCREW IMPELLER

D_j / mm	d_j / mm	S_1 / mm	P' / mm
460	140	145	575

C. Aeration System Design

The main organic substances involved in the aerobic compost reaction can be divided into nitrogenous organics ($C_{12}H_{16}O_6N$) and non-nitrogenous organics (C_2H_3O). Its reaction formula [10] is:

$$3C_{12}H_{16}O_6N+20O_2 \rightarrow C_{15}H_{18}O_4N+21CO_2+12H_2O+2NH_3 \quad (2)$$

$$4C_2H_3O+9O_2 \rightarrow 8CO_2+6H_2O \quad (3)$$

Assuming that nitrogen-containing organic matter accounts for 20% of non-nitrogen-containing organic matter, it can be seen that the mass of oxygen required for each kilogram of volatile solids is 1.498 kg. When the reaction tank is filled with 4/5 during the composting test, the material is 44kg, the initial test moisture content is 60%, the organic matter degradation rate is 35%, the mass fraction of oxygen in the air is 23.2%, and the air density under standard conditions is $1.207 kg/m^3$.

The theoretical ventilation [7] is:

$$V_{air} = \frac{1.498 \times (1-W_M) \times M_m \times V_M \times K_V}{m_o \rho_a} \quad (4)$$

where W_M is the initial test moisture content in the reactor; M_m is the mass of the stack in the reactor in Kg; V_m is the compost material organic matter content; K_V is the degradation rate of organic matter; m_o is the mass fraction of oxygen in the air; ρ_a is the density of air in kg/m^3.

After calculation V_{air} is $23.06m^3$, as the aeration system adopts the intermittent ventilation mode, the actual ventilation time of the fan can be accumulated as a result of the conversion calculation and the ventilation flow at this stage is 1.33L/min .

Another function of ventilation is to remove excess water, and calculate the air humidity and moisture evaporation of the air inlet and air inlet, thereby obtaining the amount of air needed to remove moisture. According to the references [10], [11], the amount of water removed during composting is M_w=20.24kg . So the amount of water removed every day is 1.69kg . By the formula [13]:

$$V_{cs} = \frac{M_p(1+\lambda)\times 10^3}{24\times 60(\rho_{55}k_{55} - \rho_{25}k_{25})} \quad (5)$$

where V_{cs} is the amount of ventilation required to remove moisture in L/min ; λ is the coefficient of fan leakage; ρ_{55} is the density of 55 ℃ saturated air in kg/m^3; k_{55} is the moisture content of 55 ℃ saturated air; ρ_{25} is the density of 25 ℃ saturated air in kg/m^3; k_{25} is the moisture content of 25 ℃ saturated air.

It is calculated that V_{cs} is 7.89L/min . The aeration rate of the aeration system shall be the sum of the oxygen demand of the aerobic composting reaction and the oxygen demand of the removed water, thus the theoretical aeration flow rate is 9.22L/min .

III. NUMERICAL ANALYSIS OF FLOW FIELD IN HELICAL RIBBON AND SCREW IMPELLER AEROBIC COMPOST BIOREACTOR

A. Control Equation

The composting material in the stirred tank is assumed that it flows in a laminar flow with incompressible fluid in the transient state, regardless of the temperature change. Its flow follows conservation of mass and conservation of momentum. Its flow follows conservation of mass and conservation of momentum, described by the N-S equations:

$$\nabla v=0 \tag{6}$$

$$v(\nabla v)=f-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\nabla^2 v \tag{7}$$

where v is the speed in $\mathrm{m/s}$; p is the pressure in Pa; ρ is the density of materials in $\mathrm{kg/m^3}$; f is the body force in N; μ is the viscosity of compost material which is $32.5\mathrm{Pa\cdot s}$.

B. Flow Computation

The 3D solid modeling of the internal flow field model of the reactor was completed through Solideworks modeling design. The multiple reference frame method (MRF) was used to process the interaction between the stationary reactor wall and the moving mixing blade. As shown in FIG. 3, the calculation area is divided into three parts that do not overlap each other. In the calculation, zone 1 and zone 3 adopt the rotating coordinate system, zone 2 adopts the stationary coordinate system, and when the mesh is divided, the tetrahedron structured grid is adopted, in which the total number of grids of zone 1, zone 2, and zone 3 is respectively: 304104 294428, 185473.

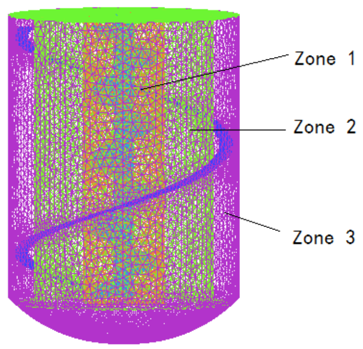
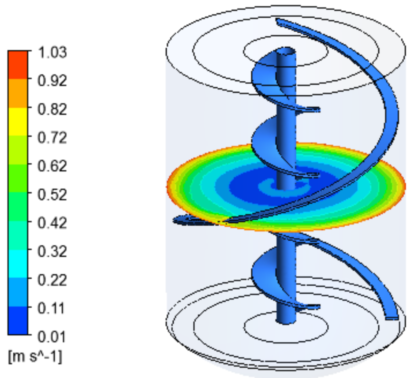


Fig. 3. Reactor grids for Zone 1, Zone 2, and Zone 3.

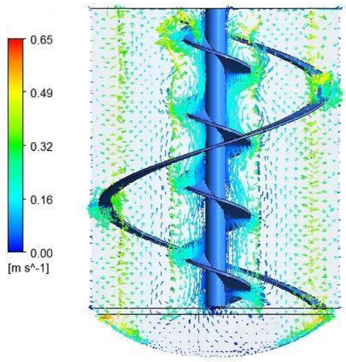
The wall surface of the reactor is a no-slip boundary condition, and the upper liquid surface is a free liquid surface, which is defined as a symmetrical boundary. The screw and screw area rotation coordinate system has the same angular velocity and the rotation speed is $40\mathrm{r/min}$. The direction is clockwise, and the stirring blade is stationary with respect to the rotating coordinate system. The reactor's internal material viscosity is set as $32.5\mathrm{Pa\cdot s}$, the density is set as $1400\mathrm{kg/m^3}$.

C. Results and Discussion

The distribution of the velocity field in the reactor is shown in Fig. 4. Figure 4-1 shows the velocity distribution of the transverse section. It can be seen from the figure that the velocity distribution gradually increases from the center to the inner wall. Figure 4-2 shows the velocity distribution of the y=0 section. One Part of the fluid near the inner wall moves towards the bottom of the reactor, and another part of the fluid appears vortex phenomenon due to the low pressure generated on the back of the blade. At the center of the reactor, opposite to the ribbon, the fluid in the vicinity of the screw rotates in a axial direction, circulating the compost material in a regular manner, thereby contributing to an increase in the ability of the center stirring and the uniformity of stirring which could efficiently achieve axial circulation of compost material.



(a) The velocity distribution of the transverse section



(b) the velocity distribution of the y=0 section

Fig. 4. Distribution of velocity field.

IV. Compost Bioreactor Performance Experiment

A. Experiment Design

In order to test the performance of the composting reactor, the body temperature, oxygen content, and seed germination index (GI) were measured at the heights of the top, middle, and bottom of the heap.

The aerobic compost experiment was conducted with cow dung and wheat straw as the main raw materials, and mushroom slag was used as the conditioning agent. Fresh cow dung was taken from experimental farms of Yangzhou University. Wheat straw was taken from farmland in Puxi Town, Yangzhou City. The wheat straw was crushed to 1-2 cm. The cow dung, wheat straw and mushroom dregs were mixed in a ratio of 4:1:1, and the appropriate water was added to adjust the initial material. The physicochemical properties of raw materials of the raw materials are shown in the table 2. The raw mixed materials moisture content was 65.76%, the carbon-nitrogen ratio was 28.53%, and intermittent aeration stirring was used. The aeration was stirred once every 12 hours.

TABLE II: PHYSICOCHEMICAL PROPERTIES OF RAW MATERIALS

Materials	Moisture content/%	Carbon content /%	Nitrogen content/%	C/N
Cow dung	76.38	38.98	1.57	24.83
Wheat straw	7.28	41.73	0.71	58.78
Mushroom dregs	29.12	42.91	1.44	29.8
Raw mixed materials	65.76	40.09	1.41	28.53

B. Variation of Temperature of Bulk Material during Aerobic Composting

As shown in Fig. 5, the temperature of the top, middle and bottom layers of the reactor can be seen from the figure. The temperature of the bulk body rises very quickly at the beginning. On the fourth day, the maximum temperature of the upper, middle and lower layers is 65.9 ℃ respectively. , 63 ℃ and 62.1 ℃. Afterwards, the temperature in each layer of the body slowly decreased. The top, middle and bottom layers exceeding 55 ℃ is 5.2, 4.7, and 4.3 days respectively. According to Kalamdhad *et al*. [14], temperature >50 °C for more than two days destroy the pathogens and sanitize the compost.

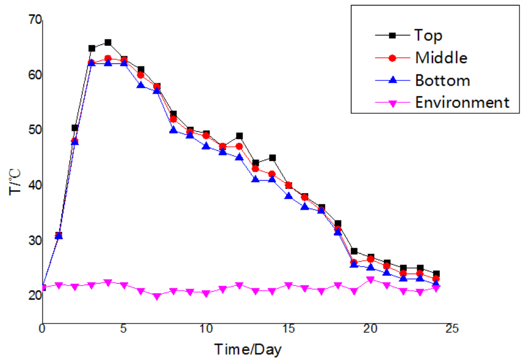


Fig. 5. Curve of temperature change during composting.

C. Variation of Oxygen Concentration in Bulk Material during Aerobic Composting

The oxygen concentration in the reactor is an important parameter to measure the fermentation efficiency of aerobic compost. As shown in Fig. 6, the oxygen concentration rapidly declines at the initial stage of composting, because at this stage, the aerobic microorganisms show an exponential growth and the microbial reproductive consumption [15]. Oxygen causes a rapid drop in oxygen concentration in the heap. From day 6 to day 12, high temperatures inhibited the growth of some microorganisms and the oxygen concentration gradually increased. After day 15, the oxygen concentration stabilized. During the whole process, the oxygen concentration in the reactor was more than 8%, and no anaerobic area was formed, which helped to suppress the generation of harmful gases [16].

D. Variation of Seed Germination Index during Aerobic Composting

The determination of seed germination index (GI) is the most effective method for determining phytotoxicity, and it is also an evaluation index for measuring the maturity of aerobic compost. In this experiment, soybean seeds (Qinong No. 1 ,Beijing Academy of Agricultural Sciences) was selected. According to the method used by Zhang Anqi et al. [7], the 5th, 10th, 15th, 20th, and 24th days were used to test the bulk materials of top, middle, and bottom layers. The root length was measured and the germination rate was counted. The results are shown in Figure 7. The final seed germination index of each layer of the stacked materials is greater than 88%, so it can be considered completely decomposed [17].

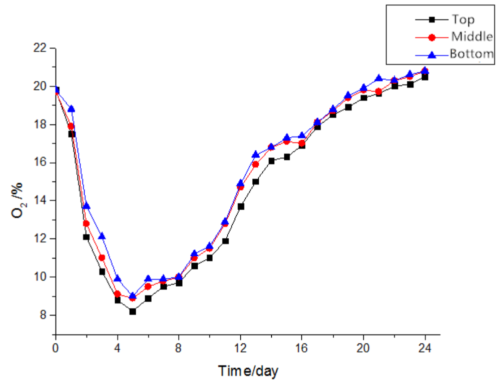


Fig. 6. Curve of oxygen concentration during composting.

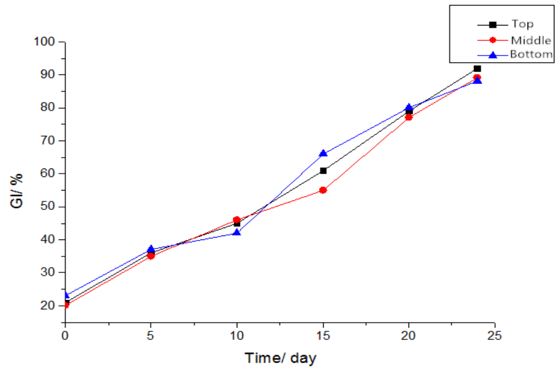


Fig. 7. Curve of seed germination index during composting.

V. CONCLUSION

1) A helical ribbon and screw impeller aerobic compost bioreactor was developed. The effective volume of the reactor was 100L. The helical ribbon and screw impeller type turning structure was used to promote axial circulation of the material and achieve homogenization.
2) Set up the helical ribbon and screw impeller geometric model and simulate the internal flow field of the reactor with Fluent to verify that the internal flow field has a good axial flow performance;
3) By measuring the temperature, oxygen concentration, and seed germination index of the top, middle, and bottom layers of the stack during the composting reaction, the time above 55 ℃ for the top, middle, and bottom layers is 5.2, 4.7, and 4.3 days. During the reaction, the oxygen concentration was over 8%, and the final seed germination index of each layer was over 88%, which proved that the experimental reactor can achieve homogenization and can be effectively harmless compost.
4) In the next part, we will establish a mathematical model of aerobic compost reaction, and apply advanced test and analysis methods, such as characterization test, to

study compost materials.

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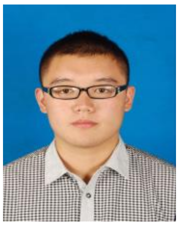

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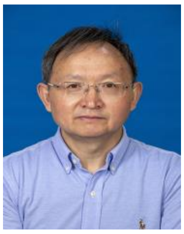

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