DESIGN AND 3-D SIMULATION OF A MIXED MODE SOLAR BARN DRIER FOR DRYING WASTEWATER SEWAGE SLUDGE

by

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The paper presents a preliminarily study on an efficient, inexpensive and energy saving solar batch dryer for drying sludge. A concept of a mixed mode solar dryer was developed and designed. Air heated by the solar flat heater was forced through drying chamber by electric fans. A 3-D physical model was used to observe and predict the operation of the solar batch dryer at different time under designed conditions. The thermal performance and air movement of drying chamber in the designed dryer unit were evaluated through ANSYS-FLUENT software. By determining the external conditions, localization and the material properties, the model can predict temperature and humidity distributions in the designed drying chamber and sludge material layers, air-flow field according to the radiation and convection, as well as water quantity evaporated from the sludge. A special attention was paid to implementation of physical boundary conditions on the sludge surface, which is between air and dried sludge. The developed solar barn dryer can heat air at average temperature between 47 °C and 57 °C, which is optimum for dehydration of the sludge. The designed drying chamber can generate an adequate fow of hot air to increase the drying rate by above 30%.

Key words: *sewage sludge, solar drying, ANSYS-FLUENT, heat and mass transfer*

Introduction

The amount of waste water sewage sludge generated in China has increased greatly, and this trend is expected to increase many folds in the years to come. The most recent data indicate a generation of 33 million tons of sewage sludge from 2500 of waste water treatment plants in China [1]. One of better ways to dispose sewage sludge is to dry it, which produces a solid that is low in humidity. The resulted solid is easily stored, reused or transported to other places. Dried sewage sludge can be employed in agriculture or forestry as organic matter, pyrolyzed or incinerated. Regarding sewage sludge drying, drying is an essential process, after application of the mechanical dewatering by centrifugation or filtration. A lower of the water content of dry solids can lead to the decrease of the cost for storage, handling and transport. In addition, drying sludge enhances the low calorific value, transforming the product into an acceptable combustible.

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Drying in open air is the most commonly used way to preserve sludge in China. Such drying under hostile climate conditions leads to an extreme low drying efficiency and possible environmental pollution. Mechanical drying is an energy consuming operation, so more emphasis should be given on using solar energy sources because of the high prices and shortages of fossil fuels. Solar dryers are now being increasingly used since they are a better and more energy efficient option. It is seen that drying rate is a strong function of air-flow or air velocity and air temperature. Previous investigation has showed that the drying rate increase significantly with air temperature and air-flow for the drying of some agriculture and fruits [2]. Therefore, it is primary necessary to know the air movement process and temperature field in solar drying chamber. Better understanding the areas of proper air-flow and high enough temperature will lead to adequate or inadequate drying.

Based on the guidelines provided by earlier researchers regarding solar sludge drying and solar agriculture drying and the results obtained in drying kinetic studies carried out for sludge [3-5], a concept of a mixed mode solar wastewater sludge dryer was developed and designed. The thermal performance and air movement of solar flat air heater and drying chamber in the designed mixed solar dryer unit were evaluated through ANSYS-FLUENT software, which also can be used as a drying optimization tool. The aim of the current work is to preliminarily study a simple efficient, inexpensive and energy saving solar batch dryer for drying sewage sludge. By determining only the external conditions, localization and the material properties, the model should predict temperature and humidity distributions in the designed drying chamber and sludge material layers, air-flow field according to the radiation and convection, as well as water quantity evaporated from the sludge.

Dryer details

Structure description of solar drier

Figures 1(a) and 1(b) illustrate the construction of the new mixed mode solar sludge drier for drying sludge. The size-scale of the drier was determined on the basis of some existing sludge drying cases in solar greenhouses and an annual amount of sludge generated in small and middle scale of wastewater treatment plants in China. The designed dimensions of the drying chamber are 25 m 7 m (Length Width), and its height is varied from 2.5 m to 7.5 m as a result of the inclination installment of five solar air heater as the top cover of the drying chamber. In order to heterogeneous thermal and humidity fields of air and sludge, three means operate. For the first one, force convection is created using exhaust fans installed in the unit, which can give a best control of the homogeneity of the air distribution in the drying chamber and homogeneous water concentration and sufficient convective transfers with the sludge. Secondly, a shuffling system regularly mixes sludge to homogenize dryness and temperature fields of these last. The central part of the shuffling system is a drum on which combs and pad-

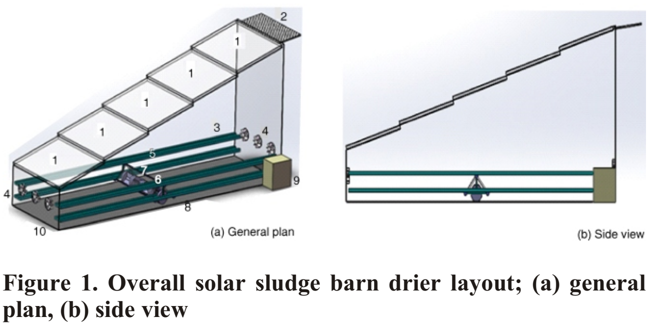

Figure 1. Overall solar sludge barn drier layout; (a) general plan, (b) side view
1 – solar flat air heater, 2 – solar electric panel, 3 – drying chamber, 4 – air exhaust fan, 5 – rotation motor left, 6 – rotation drum, 7 – running wheel, 8 – driving chain, 9 – main switch board, 10 – false floor

dles are fixed to assist in the aeration of lower layers of the sludge solid. The drum can be lowered from a free height of 50 cm to the false floor with a central motor and two toothed racks which are mechanically linked. The drum turns with a variable frequency and conveys sludge below which a slowly moving. The system can move and rotate in both directions and be controlled by frequency driven motors. Some sensors are provided to control the machines movement. Thirdly, solar air flat heaters, representing one of the main parts of the drier, are installed on the top of the drying chamber. The solar air heater and horizontal plane is into a 14° angle. The design of the air heater is simple, and its dimension of each one is 10.1 m 7 m 0.127 m (Length Width Height). It consists of a flat plate solar collector, transparent glass used as a cover, insulation (glass wool) and frame (steel). The bottom of solar air heater is made of a 0.008 mm thick aluminum plate painted in black to enhance the radiation exchange between the surface and the air, and evenly impart heat to the flowing air through that volume. The ventilation facilities were installed and designed to provide uniform air distribution over the surface of the sludge through six exhaust fans. The air-flows from one side of the solar air heater into drying chamber. The solar electric panel system was designed and installed to capture the Sun's energy using photovoltaic cells. The cells convert the sunlight into electricity, which can be used to run drying chamber appliances, lighting and shuffling system.

Principles of the sludge drying process

The solar drier is a mixed mode of direct and indirect solar using, and has to take into account all the coupled heat transfer occurred in the drying chamber. The combined action of the solar radiation incident on the dried sludge and the heat convection between the air preheated in solar tunnel heaters and the dried sludge provides the main heat needed for the drying process. The air was heated using the solar flat air heaters, and then forced into the drying chamber by centrifugal exhaust air fans. Dewatered sludge was spread over the false floor surface. The heat convection process between the heated air and sludge could be controlled through the inlet air temperature and air-flow velocity surrounding the dried materials. Solar radiation from the transparent side walls reaches sludge layer directly, and delivers heat required to evaporate residual humidity. Water evaporated out from the surface of sludge is removed from the drying chamber by the flow of ventilation air.

Air exhaust fans selection

According to a previous study regarding solar sludge drying under a forced convection mode [4], a minimum air-flow 5 m^3/s was selected for sludge drying process. The number of fans installed in drying chamber were calculated referred to the database from University of Minnesota Minneapolis, Minn., USA, Fan Selection for Grain Bins [5]. Based on the bottom dimensions of the solar drier (25 m 7 m), the bin diameter was 48.9 feet, and grain depth (sludge, 0.5 m) is 1.6 feet. The estimated fan requirements include Bin capacity of 30.049 bushel, total air-flow of 30.049 cfm, and estimated fan power needed 61 hp. A 10 hp CALDWELL C27-101-103/1750 rpm (centrifugal) fan was selected, and the number of fans on bin was 6. Fans arrangement is a parallel form.

Mathematical model and simulation procedure

The 3-D mixed mode solar sludge dryer is simulated using a CFD. The simulation analysis is performed for a summer day (August 1, 2015) for Hangzhou region in Zhejiang Province, China. Some different times of day for this simulation are selected, 11:00 a. m., 11:30 a. m., 12:00 p. m., 12:30 p. m., 1:00 p. m., 1:30 p. m., 2:00 p. m., 2:30 p. m., 3:00 p. m.,

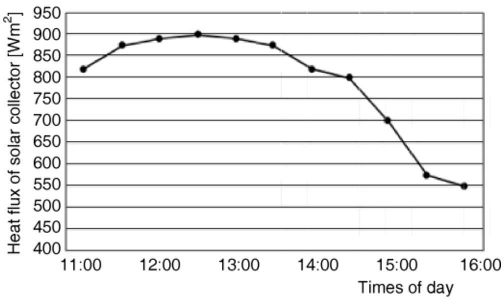

Figure 2. Heat flux of solar flat plate air heater at different times of the modelled day August 1st, 2015

3:30 p. m., 4:00 p. m.The proposed models mainly include heat and mass transport: between the inlet air and solar flat plate air heater, within the ambient air in drying chamber, within the dried material (sewage sludge), on the border of the ambient air and sludge, between the solar energy and sludge. Due to the fact that thermodynamic characteristics of the sludge as well as drying conditions (intensity of solar radiation, temperature and humidity of ventilation air) change over time, the thermal and flow processes occurring inside a dryer should be consider unsteady.

Heat transport between the inlet air and solar flat plate air heater

The solar radiation which falls on top of the glass cover is the total heat gain for the solar air heater to heat the moving air inside it. A turbulent k-ε model is used for the analysis. Heat transfer between the flowed air and solar flat collector was calculated based on the heat convection between the flowed air and solar air heater. The heat flux of solar flat collector was calculated using a clear-day solar radiation model programmed by MATLAB, shown in fig. 2. The model has been confirmed to be reliable and accurate enough to calculate a heat flux of the total solar radiation on vertical and horizontal surfaces. The weather data for the simulations were extracted from the Weather Underground, LLC [6], as showed in tab. 1. The climate data and heat flux values as a function of different times of a day were also programmed in a user-defined function (UDF) file.

Table 1. Climate data of Hangzhou at August 1st, 2015 [5]

Times of day	Temperature [K]	Humidity [%]	Times of day	Temperature [K]	Humidity [%]
11:00 a. m.	308	41	2:00 p. m.	310	29
11:30 a. m.	309	37	2:00 p. m.	309	35
12:00 p. m.	309	34	2:30 p. m.	309	34
12:30 p. m.	310	30	3:00 p. m.	307	37
1:00 p. m.	310	30	3:30 p. m.	308	46
1:30 p. m.	310	29	4:00 p. m.	308	47

Heat and mass transport of the air in drying chamber and dried sewage sludge

To simulate the process of heat and mass transfer of the air around the wet sludge, a few fluid mechanics equations such as turbulent flow-continuity equations, momentum equation, and substance transportation equation are necessary to be solved. The mentioned fluid is humid air.

Water diffusion rate in the wet sludge was obtained by the unsteady diffusion equation. A few references were referred to analyze and calculate the diffusion co-efficiency of water in the wet sludge and thermodynamic properties of the dried sludge at different temperatures and water content [7-9]. Heat transfer in the wet sludge is determined by the Fourier's law. The specific heat is calculated with the eqs. (1) and (2):

$$D(X,T) \quad D_0 X^a \exp \quad \frac{b}{T} \tag{1}$$

$$c_{\mathrm{p}}(X) \quad \frac{X}{1 \quad X} c_{\mathrm{pw}} \quad \frac{1}{1 \quad X} c_{\mathrm{s.\,m.o.}} \tag{2}$$

where $c_{\mathrm{s.\,m.\,o}} = 1434 + 3.29t$

Relation between the heat conductivity of the sludge and its water content can be described with the eq. (3):

$$\lambda(X) \quad 0.5148\,\mathrm{e}^{\;0.0051X} \tag{3}$$

Modelling air-sludge border

ANSYS-FLUENT software does not contain standardized boundary condition type, such as simultaneous mass and heat transfer processes occurring at a physical border between sludge and gaseous phases. To achieve an appropriated calculation conditions, the drying process and performance of the dried sludge were studied by incorporating UDF in FLUENT written in C language. The UDF are used to adapt the boundary condition, model variable material properties, and new source components in transport equations or calculations initialization. Such functions allow to extend models provided in the basic FLUENT software package. Moisture was considered as a user-defined scalar (UDS) to simulate the distribution of moisture inside the porous bed.

Simulation procedure

For the simulation needs, a complete 3-D model was developed based on the designed solar sludge drier, as shown in fig. 1. For the geometry, a control volume was selected to represent a large domain including solar air heater, drying chamber, and sludge material layer. The grid structure was hexahedral computational cells. The final grid has 506.280 nodes, 3 cell zones and 26 face zones. The grid was subjected to grid independence tests and ensure the solution independency from numerical errors due to spatial discretization. In addition, mesh properties like the minimal angle for each element and relative determinant of the mesh were extensively studied. Grid quality was checked by considering the cell aspect ratio, cell equi-angle skew, and cell growth factor.

The boundary conditions used for simulation of ambient conditions and solar radiation were based on average values from the meteorological station of Hangzhou. The modelled ambient conditions and solar radiation were varied along with different times of a day, which the boundary conditions were programmed in UDF files. The basic assumption relating to the transport moisture modelling takes the air as a mixture of dry air-vapor. Furthermore, no chemical interaction exists between these two sorts, and their mixture is assumed as an ideal gas. As a result, the vapor represents a scalar transported by the air-flow, but at the same time, the water vapor properties influence the air-flow governing equations. At the inlet of the computational geometry, a logarithmic inlet velocity profile (atmospheric boundary-layer model) was considered [10,

Table 2. Simulation settings in the numerical model

Description	Method/value
Geometry and grid	
Geometrical space	3-D
Maximum grid aspect ratio	3.29944
Maximum cell growth factor	1
Maximum equi-angle skew	0.38
Porous bed section area, [m^2]	24 6.5
Drying chamber inlet section area, [m^2]	5 air inlets, 7 0.127
Drying chamber height, [m]	from 2.5 to 7.5
Materials	
Sludge density, [Kgm^{-3}]	1300
Sludge heat capacity, [JKg^{-1}k^{-1}]	1.244
Sludge thermal conductivity, [Wm^{-1}K^{-1}]	0.8
UDS (moisture) diffusivity in gas phase	Defined-per-UDS
Operation, boundary condition, and initial conditions	
Operation pressure, [Pa]	101325
Gravitational acceleration, [ms^{-2}]	9.81
Inlet boundary condition, [ms^{-2}]	Velocity inlet, 5
Outlet boundary condition	Pressure outlet, zero gage pressure
Viscous resistance of porous zone [1 m^{-2}]	2.111 10^{15} (3 directions)
Inertial resistance of porous zone [1 m^{-2}]	1860506 (3 directions)
Fluid porosity	0.2
Solution	
Solver	Pressure based
Discretization method	First-order upwind
Time step, [s]	180
Unsteady formulation	Second-order implicit
Maximum number of iteration per time step	30
Convergence criteria	0.001
Under-relaxation factors	0.3-0.8

11]. The air velocity (at a reference height) and the air temperature and humidity are given as known values using the values of the meteorological mast, as shown in tab. 1 and fig. 4. The air-flow in porous zone (sludge) was laminar. The standard k-ε turbulence model was considered at the drying chamber. The complete simulation setting is listed in tab. 2.

Results and discussions

Because the air movement phenomena in the modeled drier system is not complex. Heated air flowed out of the solar air heater and spreads over the drier sludge surface. Two selected distributions of air temperature within the modelled geometry for initial time and final time of the modelled day are presented in figs. 3(a) and 3(b), respectively. It can be seen that air temperature is continuously increased as it flows away from the exit along with the length of the solar flat air heater, and air temperature in main drying chamber is higher than that in sludge layer. The highest temperature of air flowing into drying chamber can reach up 365 K, and the average temperature of air in drying chamber is 316 K.

However, it was not found that a large difference amount the air temperature distributions in drying chamber at different times of the modelled day. Even if it was at 16:00 hour of the modelled afternoon, the air temperature distribution in drying chamber is almost as high as that at 11:30 hour of the modelled morning. A typical contour of air velocity distribution in the modelled geometry is provided in fig. 4. The contour explains the non-uniform, 3-D distribution of air movement. Because of the rapid change in cross-section of the drying chamber from the left to the right, the air flowing into the chamber has a relatively

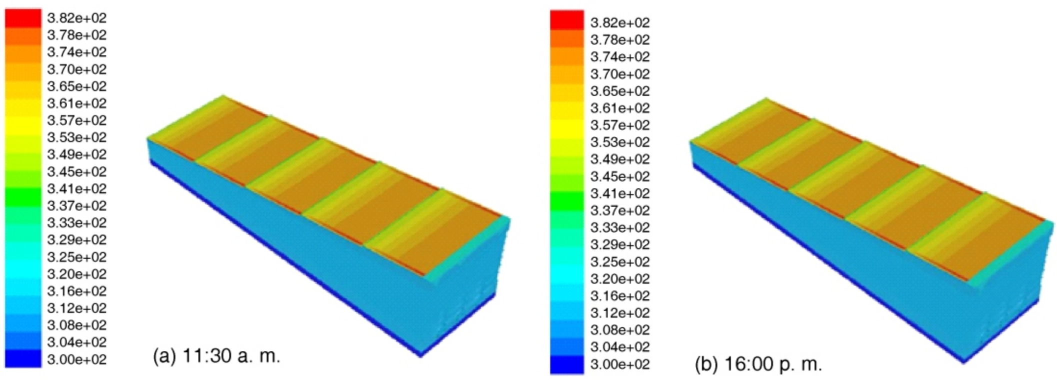

Figure 3. Distribution of air temperature at various times of the modelled day

higher velocity at the center, and the air velocity on the left chamber is a little lowerthan air velocity on the right.

A typical contour of relative humidity distributions in the dried sludge and drying chamber are provided in figs. 5(a) and 5(b). It can be noted that water content of the dried sludge has an obvious change as a function of sludge bed depth. The moisture of the dried sludge for 16:00 hour of the modelled day is obviously decreased compared to the modelled initial time. Figure 6 shows the relative humidity of the dried sludge at different bed depth as a function of dry-

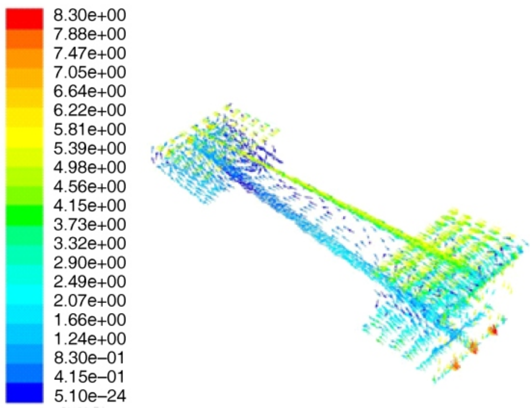

Figure 4. Air velocity distribution in the modelled geometry

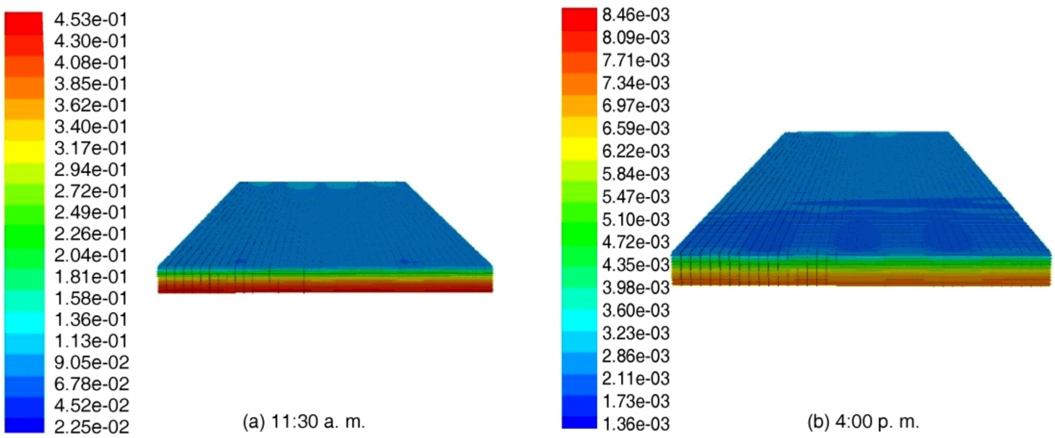

Figure 5. Relative humaidity in dried sludge layer for various times of the modelled day

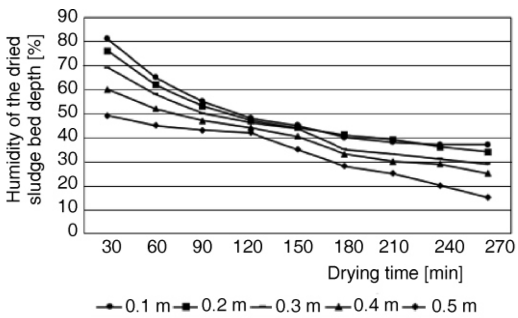

Figure 6. Relative humidity of sludge at different bed depth as a function of drying time

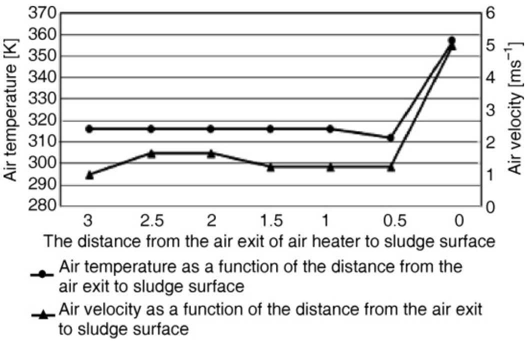

Figure 7. Air temperature and air velocity as a function of the distance from the air exit of air heater to sludge surface

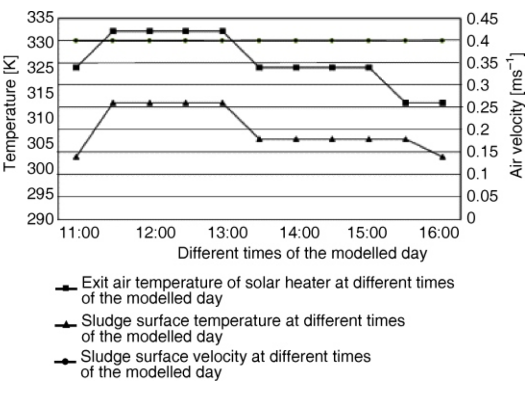

Figure 8. Air temperature of solar air heater, and sludge surface temperature and velocity at different time of the modelled day

ing time. The depth of the applied solid matter is one of the main factor influencing sludge drying process. Feed sludge with a high amount and deep layer would result in a slower drying time. If the applied depth is too shallow, the thickness of the sludge layer will be small and more application area will be required for a certain volume of sludge. If the applied depth is too thick, there is a risk of sludge gluing and physical damage to the sludge shuffling system.

The surround environmental conditions have the most influence on the drying process and drying rate. These surrounding environmental conditions for drying sludge in our case mainly include air temperature, air velocity and ventilation flux on the surface of sludge. Figures 7 and 8 show that air temperature and air velocity as a function of the distance from the exit of air heater to sludge surface, and sludge surface temperature and velocity at various times of the modelled day.

Modeling results indicate that the sludge humidity was basically evenly decreased along with drying time. The sludge humidity at different depth is inversely proportional to the drying rate. The lowest air velocity value occurs below the first heater.

Conclusions

In this study, a greater emphasis is given to use solar energy sources for sludge drying, due to the high energy price and shortage of fossil fuels. For the purposes, a new natural solar dryer mainly consists of solar flat air heater, drying chamber, air exhaust fan, false floor was developed. A preliminary 3-D simulation was conducted using ANSYS-FLUENT software to investigate the distributions of air temperature, humidity and velocity in the drying chamber, and drying rate of sludge.

The results of FLUENT simulation study indicate a potential of using this approach to describe and predict the trends and performance of a solar sludge drier. The developed solar barn dryer can heat air by the average temperature between 47 °C and 57 °C, which was optimum for dehydration of the sludge. This drying chamber can generate an adequate flow of hot air to increase the drying rate. Various design features can be added to the basic design to further compare and optimize the solar drier. During the simulation calculation by FLUENT software, the unsteady-state simulation of the heat and mass transfer phenomenon during sludge drying is straightforward. Many practical problems are occurred by the coupling of several different heat transfer equations, the existence of a solid phase and a fluid phase. The employed heat transfer equations, moisture evaporation equation and so on are not very accurate because they are obtained from drying process of biomass. In terms of sludge drying simulation, little relative equations can be found and used for moisture evaporation of sludge from published literatures.

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