Ecological Engineering 64 (2014) 269–275

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Design and control of rotating soil-like substrate plant-growing facility based on plant water requirement and computational fluid dynamics simulation

Dawei Hu[a,b,*], Liang Li[a,b], Hui Liu[a], Yi Sun[a], Leyuan Li[a], Yuming Fu[a], Houkai Zhang[a,b]

[a] Lab of Environmental Biology and Life Support Technology, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China

[b] State Key Laboratory of Virtual Reality Technology and Systems, School of Computer Science and Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 18 August 2013
Received in revised form 6 December 2013
Accepted 22 December 2013
Available online 28 January 2014

Keywords:
Soil-like substrate
Lettuce cultivation
Centrifugal force
Precise irrigation
CFD simulation

ABSTRACT

It is necessary to process inedible plant biomass into soil-like substrate (SLS) by bio-compost to realize biological resource sustainable utilization. Although similar to natural soil in structure and function, SLS often has uneven water distribution adversely affecting the plant growth due to unsatisfactory porosity, permeability and gravity distribution. In this article, SLS plant-growing facility (SLS-PGF) were therefore rotated properly for cultivating lettuce, and the Brinkman equations coupled with laminar flow equations were taken as governing equations, and boundary conditions were specified by actual operating characteristics of rotating SLS-PGF. Optimal open-control law of the angular and inflow velocity was determined by lettuce water requirement and CFD simulations. The experimental result clearly showed that water content was more uniformly distributed in SLS under the action of centrifugal and Coriolis force, rotating SLS-PGF with the optimal open-control law could meet lettuce water requirement at every growth stage and achieve precise irrigation.

1. Introduction

Soil-like substrate (SLS) preparation is essentially a composting process via the synergetic action of earthworms and bacterial microflora under the artificially controlled environment. In this course, the macromolecular organic matter in inedible plant biomass is degraded into the micromolecular organic matter while simultaneously releasing biogenic mineral elements like nitrogen, phosphorus, potassium for the next circulation, imitating the formation process of a natural soil system for sustainable plant cultivation (Manukovsky et al., 1997; Nesterenko et al., 2009; Tikhomirov et al., 2003a; Hu et al., 2013). Compared with other treatment processes of inedible plant biomass such as incineration, anaerobic and aerobic fermentation, acid extract and enzyme conversion, SLS has many advantages in the aspects of productivity, degradation extent, energy efficiency, operation stability, environmental friendliness and safety. Hence SLS could be extensively used in ground eco-agriculture and space life support system (Tikhomirov et al., 2003b; Gitelson et al., 2003; Gros et al., 2005; Liu et al., 2008; Hu and Liu, 2012).

SLS is a typical porous medium similar to natural soil, and therefore water and dissolved nutrient substances available will move from the inside of SLS to plant roots under the joint action of capillary power and gravity force, meeting the plants growth requirements. However, because the formation time is relatively shorter in contrast with the natural soil system, SLS has inevitably some deficiencies in porosity, permeability, water holding capacity, etc. Hence unbalanced supply-demand of water and dissolved nutrient substances caused by uneven water distribution often adversely affect the plant growth on SLS. Nevertheless, less attention has been currently paid on how to make water be more uniformly distributed in SLS under long-term continuous operation conditions, which should be encountered in ground- and space-related applications in the future.

In our research, more uniform water distribution in SLS was achieved by appropriate rotation of SLS plant-growing facility (SLS-PGF) for lettuce cultivation on a horizontal axis. Based on governing equations coupling Brinkman equations to laminar flow model, specific geometric configuration and boundary conditions,

Abbreviations: CFD, computational fluid dynamics; SLS, soil-like substrate; PGF, plant-growing facility; PWSP, porous water supply pipe; RWD, reference water demand.

* Corresponding author at: Lab of Environmental Biology and Life Support Technology, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China. Tel.: +86 10 8233 9872; fax: +86 10 8233 9872.
E-mail address: dwhu@163.com (D. Hu).

0925-8574/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2013.12.048

the optimal open-loop control law of angular velocity of rotation generating centrifugal force and Coriolis force and the inflow velocity of porous water supply pipe (PWSP) was obtained to continuously manipulate the water distribution in SLS to satisfy lettuce's changing water requirement (Sirivithayapakorn and Keller, 2003; Auset and Keller, 2004). The prototype experiments demonstrated the validation of modeling and simulation, the rotating SLS-PGF with the optimal open-loop control law and corresponding precision irrigation technology according to plant real-time water requirement therefore could be widely employed in agroecological engineering field for high-efficiency plant cultivation on SLS in water-deficient conditions such as the polar regions, deserts, mountainous regions, outer space, lunar and Mars base, and so forth.

2. Materials and methods

2.1. Prototype of rotating SLS-PGF

The inedible wheat biomass, mostly straw, bran and roots, was smashed and uniformly mixed together for the SLS preparation lasting about 90 days via a compost reaction under the combined action of earthworms (*Eisenia foetida* Savigny) and aerobic bacterial microflora in the artificial environment (Yu et al., 2008; He et al., 2010; Kang et al., 2012). Lettuce (*Lactuca sativa* L.), a popular vegetable and an important space food satisfying astronauts' needs for fresh vitamins and rough dietary fibers (Lazic et al., 2002), was cultured on SLS by a rotating SLS-PGF prototype mainly included fixed and rotatable components.

The fixed component consisted of artificial light source and temperature modulator. The 1566 light emitting diodes (LED) designed with 872 red (660 nm) and 694 white (2700 K) lights were selected as artificial light source keeping 24 h illumination with average light intensity of $350 \pm 50\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$. The 8 fans were taken as temperature modulator to maintain the temperature of $23 \pm 2\,^{\circ}\text{C}$ consistently. Additionally, other environmental parameters including relative air humidity of $33 \pm 2\%$, ambient CO_2 of 350 ppm and the irrigating water of 1/2 concentration Hoagland solution with pH of 6.5 were implemented throughout the experimental period.

The rotatable component containing a cylindrical cultivating surface and a PWSP was designed with two coaxial cylinders and rotated with a certain angular velocity by an electromotor. The cylindrical cultivating surface was comprised of 6 identical ring-shaped SLS cultivating modules, and each of them has 6 planting holes for the cultivation of an individual lettuce. These parts were assembled to the central PWSP. Except the walls of PWSP directly contacting with the SLS cultivating modules were porous to ensure free outflow of irrigating water, the rest walls were watertight. The irrigating water introduced from PWSP continuously permeated the SLS to provide lettuce. Except for planting holes position, the outer covering of the SLS cultivating modules was also impermeable to prevent the SLS from drying out. The Sectional views of rotating SLS-PGF and the size of each part were illustrated in Fig. 1.

2.2. Mathematical modeling and digital simulation

In order to deeply investigate the complicated water distribution in the rotating SLS-PGF, the governing equations expressed in terms of a set of parameterized partial differential equations were developed based on porous media theory and CFD (Hossain and Wilson, 2002; Homicz, 2004; Comsol Inc, 2012). Boundary conditions including *Dirichlet* and *Neumann* conditions were properly specified according to the actual operating state of rotating SLS-PGF.

According to specific geometric configuration, governing equations, boundary conditions and prescribed dynamic performance specification of rotating SLS-PGF, on the platform of Comsol Multiphysics and Matlab, a large amount of digital simulations were conducted to investigate flow fields characteristics in different domains of rotating SLS-PGF, discretely optimize time-variant control parameters, and ultimately obtain the optimally continuous-time open-loop control law by B-spline interpolation (Mathworks Inc, 2010; Comsol Inc, 2012).

3. Results and discussion

3.1. Hypothesis in modeling rotating SLS-PGF

The partial differential equations governing the coupled transfer processes of water in rotating SLS-PGF were derived according to the following assumptions:

- SLS was fundamentally composed of porous media domain and free flow domain. Global momentum transport of irrigating water by shear stresses could be negligible in the porous medium.
- Irrigating water in both PWSP and SLS could be considered as a dilute solution, and all points of the inside of the rotating SLS-PGF were therefore identical in fluid density and viscosity.
- Geometric configuration of rotating SLS-PGF was symmetric, so the modeling domains could be reduced to 2D without dramatically reducing the validity of the calculation and simulation.

3.2. Governing equations and boundary conditions

3.2.1. Governing equations in PWSP

The irrigating water flow in the PWSP was regarded as laminar flow due to relatively slow flow speed with small Reynolds number (less than 2000), and the fluid flow in the PWSP was therefore described by the incompressible Navier–Stokes equations for the velocity field as follows:

$$\rho\left[\frac{\partial \mathbf{u}_1}{\partial t} + (\mathbf{u}_1 \cdot \nabla)\mathbf{u}_1\right] = \nabla \cdot [-p_1\mathbf{I} + \mu(\nabla\mathbf{u}_1 + (\nabla\mathbf{u}_1)^T)] + \mathbf{F}_1 \quad (1)$$

$$\nabla \cdot \mathbf{u}_1 = 0 \quad (2)$$

where $\mathbf{u_1}$ ($\text{m}\,\text{s}^{-1}$) and p_1 (Pa) were the dependent variables, denoting the flow velocity and the pressure in the PWSP, respectively. The ρ ($1.08 \times 10^3\,\text{kg}\,\text{m}^{-3}$) and μ ($1.34 \times 10^{-3}\,\text{kg}\,\text{m}^{-1}\,\text{s}^{-1}$) measured experimentally represented density and dynamic viscosity of the irrigating water, respectively. Influences of gravity and other volume forces like centrifugal force and Coriolis force on water distribution in PWSP were accounted for via the force term $\mathbf{F_1}$ containing two components: in *x* axis direction, $\mathbf{F_{1x}}$ equaled to Coriolis force, and in *y* axis direction, $\mathbf{F_{1y}}$ was the sum of gravity and centrifugal force.

$$\mathbf{F_{1x}} = 2\rho\omega \cdot \mathbf{u}_1 \quad (3)$$

$$\mathbf{F_{1y}} = -\rho(\mathbf{g} + y\boldsymbol{\omega}2) \quad (4)$$

where $\mathbf{g}$ ($9.81\,\text{m}\,\text{s}^{-2}$) denoted gravitational acceleration, $\boldsymbol{\omega}$ was both the angular velocity –of rotating SLS-PGF and a time-variant control parameter required being specified by instantaneous water requirements of lettuce at different growth stages and digital simulation.

3.2.2. Governing equations in SLS cultivating module

Brinkman equations were selected as governing equations of momentum transport of irrigating water in SLS cultivating module