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Heat transfer in packed-beds of agricultural waste with low rates of air flow applicable to solid-state fermentation

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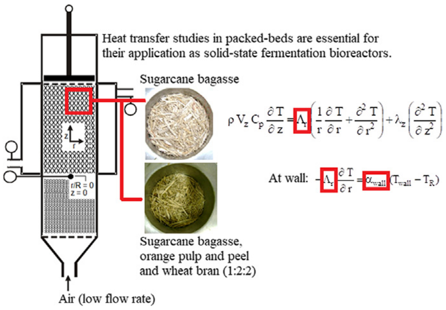
HIGHLIGHTS

- Paper addressed heat transfer in beds packed with agricultural waste.
- Air flow rate and bed height markedly affected radial temperature profiles.
- Beds of sugarcane bagasse are non-favorable for heat transfer.
- Mixture of particles of different shapes and sizes improves heat transfer.
- Thermal parameters are useful for reliable simulation of bioreactors.

GRAPHICAL ABSTRACT



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ABSTRACT

Heat transfer studies were carried out in packed-beds (PBs) heated by the wall and percolated by low air flow rates. Porous media were composed by particles of sugarcane bagasse (SCB) and by a mixture of particles of SCB, orange pulp and peel (OPP) and wheat bran (WB) at proportion SCB:OPP:WB 1:2:2 w/w (composed medium), agricultural waste used as substrates in bioreactors of solid-state fermentation (SSF), an interesting biotechnological application of PBs. Once metabolic heat generated has to be dissipated, heat transfer studies and thermal parameters are required. Tube-to-particle diameter ratio was $D/d_p = 260$, bed height ranged from L = 60 to 180 mm, while air flow rate ranged from 400 to 1200 L/h. Air temperature was 40 °C and wall temperature 65 °C. The outlet bed temperatures (T_L) were measured by ring-shaped sensors and by aligned thermocouples. Average temperatures (T_{avg}) and global heat transfer coefficients (U) were calculated separately for central region of the beds and for wall-vicinity. Radial effective thermal conductivity (Λ_r) and wall-to-fluid convective heat transfer coefficient (α_{wall}) have been estimated by means of the traditional two-parameters model. Radial temperature profiles at bed outlet were flattened in the central region and convergent at the edge of the packs. The two-regions approximation for U calculations showed to be appropriate for both packs. Global coefficient U, thermal conductivity Λ_r and convective coefficient α_{wall} increased with increasing air flow rate and decreased with bed height. Λ_r tended to the stagnant value of the thermal conductivity and α_{wall} were lower than 50 W/m^2/°C, addressing the difficulty on removing metabolic heat from PBs of SSF.

1. Introduction

The study of heat transfer in fixed beds packed with a porous solid matrix percolated by a fluid is basic for comprehension of

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thermal phenomena in particulate systems, which are widely used in important unit operations in chemical and food industries. Applications examples include the use of packed-beds (PBs) as separators, absorbers, dryers, filters and heat exchangers (Thoméo and Freire, 2012; Wen and Ding, 2006), besides to be very frequently used as chemical and biochemical reactors, where strongly exothermic irreversible reactions take place. For reactors, the study of heat transfer become even more relevant, once the knowledge of temperature profiles is necessary for a better understanding of chemical and biochemical reactions rates and yields (Thoméo et al., 2004).

A specific application of this kind of fixed beds is their use as packed-bed bioreactors (PBBs) for solid-state fermentation (SSF), a biotechnological process in which agro-industrial by-products are applied as substrates to produce high-added value products, such as several types of enzymes. In other words, by means of SSF, primary or secondary biotechnologically interesting metabolites are released as consequence of the metabolic activities of microorganisms cultivated on a moist solid porous matrix. The water content does not exceed the water retention capacity of the porous media, hence there is no dripping water filling the inter-particle spaces, which in turn are filled with a continuous gas-phase (Durand et al., 1998; Pandey, 1992).

In PBB for SSF, heat transfer studies are also essential, once it is necessary to dissipate the metabolic heat generated by the respiration of the microorganism along the cultivation, in order to maintain the ideal operational conditions for microbial growth and consequent release and preservation of the interesting metabolites (Mitchell et al., 2000). Concerning the airflow rates in SSF systems, although higher airflow rates could be expected to improve metabolically generated heat removal from inside the PBB during the cultivations (Ghildyal et al., 1994), low airflow rates are usually applied due to avoiding the drying of the porous media because of air percolation, which might harm the microbial growth (Casciatori et al., 2016).

The mathematical modeling of heat transfer mechanisms in beds packed with particles from agricultural waste commonly used as substrates in SSF and the simulation of such fermentative systems by solving the models are shown as useful tools for designing and controlling SSF bioreactors. By means of modeling and simulation, it is possible to predict thermal profiles and probable hot spots along the cultivations, as well as to propose operational alternatives on how to avoid overheating within the PBBs (Casciatori et al., 2016; Fanaei and Vaziri, 2009; Mitchell et al., 1999; Sangsurasak and Mitchell, 1995a; 1995b; 1998; Saucedo-Castañeda et al., 1990; Von Meien and Mitchell, 2002).

Such models depend fundamentally on the knowledge of the thermal properties of the porous matrices used as substrates and percolated by air. However, experimental information required by the models are still scarce in literature (Ashley et al., 1999), leading to the use of very hard considerations that consequently give simulated results far from the experimental ones. In this context, the current paper addresses the determination of the radial effective thermal conductivity (Λ_r) and of the convective heat transfer coefficient wall-to-fluid (α_{wall}) in fixed beds percolated by low airflow rates and packed with porous matrices interesting to SSF, aiming to provide thermal parameters values close to the experimental reality for the heat transfer models in SSF systems, aiming to increase the accuracy of simulation of such processes.

Two porous matrices have been studied in the current paper: the first one composed by sugarcane bagasse (SCB) and the second one composed by a mixture of sugarcane bagasse (SCB), orange pulp and peel (OPP) and wheat bran (WB) at proportion SCB:OPP:WB 1:2:2 w/w. The use of SCB in SSF is common and feasible mainly in Brazil, where this by-product of sugar and alcohol industry is abundant, and it has low commercial value (Soccol, 1995). Besides the economic advantages, SCB is a good source of cellulosic carbon, inducing the production of cellulolytic enzymes by the microorganism cultivated, as well as it has a fibrous structure, resulting in porous matrices with high porosity, which is desirable in PBs applied to SSF because of allow appropriate supply of oxygen to the microorganism within the bed.

The composed media SCB:OPP:WB 1:2:2 w/w here studied was employed by several authors to produce by SSF pectinolytic enzymes, largely used in food industry, mainly citric juices industries (Martin et al., 2004, 2010; Umsza-Guez, 2009). Once there is a great interest in the scale-up of this production, engineering studies giving support to the development of pilot and industrial bioreactors are required, justifying the determination of thermal parameters of beds packed with the agricultural waste chosen in the current paper.

1.1. Effective thermal properties of porous media percolated by air

The effective thermal properties of a porous medium percolated by air, such as Λ_r and α_{wall} studied in this paper, comprise several heat transport mechanisms: heat conduction trough the solid particles, heat conduction trough the liquid stagnated in contact with the particles, convection particle-fluid, thermal dispersion in fluid phase, heat conduction between wall and particles and convection wall-to-fluid (Laurentino, 2007; Thoméo, 1990). In general, such effective thermal parameters are obtained by means of experimental spatial profiles of temperatures followed by non-linear parameters fitting.

There are two ways of modeling thermal phenomena in PBB: the two-phase or heterogeneous or the single-phase or pseudo-homogeneous approaches. The two-phase model comprises a specific equation for each phase, by considering either solid and gas phases have specific dynamics of heat transfer. However, this model is difficult to be applied, due to the problems on the experimental measurement of the temperature in each phase (Kunii and Suzuki, 1967). With computational advances, many papers have been published by applying CFD (Computational Fluid Dynamics) tools, which enables to estimate heat transfer coefficients by simulation employing the two-phase model, although it is not possible to make experimental validation (Augier et al., 2010; Guardo et al., 2005).

The one-phase model considers that, for a representative volume element of the pseudo-homogeneous medium, the temperatures of both phases are the same, which simplifies the experimental measurements, once it is enough to be measured the fluid temperature for the thermal parameters of this model can be determined. Controversial issues of this approach are the level of details of the model (Coberly and Marshall, 1951; De Wash and Froment, 1972; Dixon, 1985), the boundary conditions of the energy balance (Dixon, 1985), the way of thermal coefficients estimative and the techniques of temperatures measurements (Thoméo et al., 2004).

Among the first studies of heat transfer in cylindrical packed-beds with monophasic flow, we find the one carried out by Colburn (1931), who measured only average radial temperatures at fluid inlet and outlet. With this, the author determined the global coefficient of heat transfer (U), defined in Eq. (1):

$$\frac{R}{2}GC_p\frac{dTavg}{dz} = U(Tavg - T_{wall}) \tag{1}$$

where R is the total radius of the bed; G is the surface mass flux of the percolating fluid and C_p its specific heat capacity; T_{avg} is the dependent variable average radial temperature; z is the independent variable axial position and T_{wall} is the tube-wall temperature, established by the cooling or heating jacket.