

Heat and Mass Transfer Study During Wheat Straw Solid Substrate Fermentation with *P.ostreatus*

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Abstract: The solid state (substrate) fermentation of the wheat straw with *Pleurotus ostreatus* is a complex process implying biological, chemical and physical phenomena linked to the fungus growth and the degradation of the straw. Heat and mass transfer during the removal of the metabolic heat and products is an interesting aspect for scaling up to high-capacity facilities. Accurate heat and mass balances help to forecast the utilities needed in the fermentation rooms. In this work, a heat and mass transfer study was worked out for this agro-industrial process at a larger scale than the standard growth of *P.ostreatus* in small plastic bags and trays. The study consisted on performing heat transfer and mass (water) transfer balances, finding the accurate description of the transfer mechanisms and calculating the transfer coefficients. The practical goal of the study was to measure the metabolic heat and the water vapour adsorbed from air, in order to design the cooling and venting utilities for the fermentation room, as well as the external spraying need.

Keywords: *Pleurotus ostreatus*, SSF, mass and heat transfer

1. Introduction

Solid Substrate Fermentation (SSF) means aerobic microbial transformation of a solid material without presence of free water because the solid is a porous matrix with a relative high activity at the water adsorption. Traditional SSF applications include the Japanese *koji*, Indonesian *tempeh*, Indian *ragi* and French "blue cheese" *roquefort*. Beside of these food applications, industrial production of different enzymes and citric acid were developed in Japan. Another important application accompanies the growth of mushrooms on compost (e.g. *Pleurotus Ostreatus* on wheat straw compost) [1], and in this case, the fermentation produces the degradation of the lignocellulosic substrate allowing to obtain high value chemical compounds for pharmaceutical use, polymers synthesis, lubricants, etc.

Small scale cultivation of *Pleurotus ostreatus* is common in the farms of South- East Asia [2]. In Europe and United States, the process was scaled up, allowing the harvesting of tons of mushrooms on tons of straw in relatively small sheds as seen in Figure 1:



Figure 1. Scale up growth of *Pleurotus ostreatus* [3]

The scaling-up is hindered by some constrains due to the microbiological metabolism: the respiration is highly exothermic; due to the poor heat transfer capacity of the substrate, heat generated by the fungal activity within the solid can lead to the overheating with the prospect of killing microorganisms and compromise the fermentation. Heat removal is probably the most important factor in scaling up SSF processes. A high flux of air would eliminate the heat transfer problem but this would damage the process because of straw drying and disruption of mycelium. Only evaporative cooling devices provide sufficient heat elimination. Also, the aeration can have a critical role in heat transfer, although the primary function of aeration was to supply oxygen for cell growth and to flush out the produced carbon dioxide.

The present work deals with the heat and moisture transfer during the mycelium growth phase. The study consisted on performing heat transfer and mass transfer balances, finding the accurate description of the transfer mechanisms and calculating the transfer coefficients. The practical goal of the study was to measure the metabolic heat and the water vapour adsorbed from air, in order to design the cooling and venting utilities for the fermentation room, as well as the external spraying needed.

2. Theoretical aspects

The growth of the mycelium is accompanied by heat generation. This heat is transferred to the environment by two mechanisms: conduction in the straw bed and natural convection. The Biot number (Bi) is the index of the heat transfer resistance inside and at the surface of a body. It is defined by (1):

$$Bi = \frac{h \cdot L}{k_b} \quad (1)$$

where: h - convective transfer coefficient, W/m^2K ; L - characteristic length (the ratio between the volume and the heat transfer surface of the body), m; k_b - thermal conductivity of the body, W/mK .

The value of the Bi number gives indication about the uniformity of the temperature inside a body. If $Bi < 0.1$, the temperature is uniform inside the body and the heat transfer is governed by convection. If $Bi > 1$, the temperature is non-uniform and conduction is the main transfer mechanism.

Because the straw bed is a heterogenous porous material, we can consider it as a pseudohomogenous system consisting of a single matrix [4,5] with the average physical properties ρ (density) and c_p (specific heat capacity) calculated with (2) and (3):

$$\rho = \varepsilon \cdot \rho_a + (1 - \varepsilon) \cdot \rho_s \quad (2)$$

$$c_p = \varepsilon \cdot c_{pa} + (1 - \varepsilon) \cdot c_{ps} \quad (3)$$

where: ε is the porosity of the bed, ρ_a is the density of the air and ρ_s is the density of the straw.

The thermal conductivity for this pseudohomogenous system can be calculated with (4), according to Hasan *et al.*[4]:

$$k_b = 47.5080 + 0.0115 \cdot \rho + 0.1295 \cdot M - 6.0737 \cdot \ln(\rho) - 5.5555 \cdot \ln(M) \quad (4)$$

where: M denotes moisture of the straw.

Modeling the heat transfer as a conduction-only transfer, an effective thermal conductivity k_{eff} can be defined [6] with (5):

$$k_{eff} = k_{eq} \cdot k_a(T) \quad (5)$$

where: k_{eq} is the equivalent thermal conductivity (6):

$$k_{eq} = Q/Q_{cond} \quad (6)$$

Q being the heat transfer rate due to conduction and convection and Q_{cond} being the heat transfer rate for conduction only.

In the equation (5), $k_a(T)$ denotes the thermal conductivity of the air which is a function of temperature. The effective thermal conductivity from (5) is equivalent to k_b in (1) and (4).

The correlation (7) between Nusselt and Rayleigh numbers for horizontal hot surfaces transferring heat in the environment is:

$$Nu = 0.54 \cdot Ra^{1/4} \quad (7)$$

where Rayleigh number defined with (8):

$$Ra = (g \cdot \beta \cdot \Delta T \cdot L_c^a) / (\nu \cdot h) \quad (8)$$

g being the gravitational acceleration, m/s^2 ; β - the thermal expansion coefficient, K^{-1} ; ν - the cinematic viscosity, m^2/s ;

ΔT - the temperature difference between the body and the environment, K ; h - convective transfer coefficient, W/m^2K ; L_c characteristic length; in this case $L_c = 2A/P$, A and P referring to the area and perimeter of the heat exchange surface.

Nusselt is defined by (9):

$$Nu = (h \cdot L_c) / \lambda \quad (9)$$

L_c being the same characteristic length as in (8).

The convective transfer coefficient can be calculated with eq. (9). With the effective thermal conductivity and the convective coefficient, the global transfer coefficient would be calculated as in case of thermal resistances in series. Then, the thermal flux from the body (bag of straw) to the air can be calculated.

These data are then used to calculate the heat balance (10) around the shed [7]:

$$H = (E_o - E_i) + dS/dt + (K \cdot dT) \quad (10)$$

where H is the heat production rate (W), E_o and E_i are the thermic fluxes carried by the air in and out, if a ventilation system is used; if not, $(E_o - E_i)$ is the thermic flux taken over by the evaporating water system; K is the apparent thermal conductivity ($W/^\circ C$) of the walls and S is the summation of all heat storage components(J), these components being: the dry matter and moisture in straw, the walls and the internal air in the shed. The apparent thermal conductivity of the walls is taken $64W/^\circ C$ for uninsulated walls, as recommended in [7].

Following the heat balance, the necessary of heat removal from the shed can be calculated and cooling through evaporation system can be dimensioned.

A material balance referring to the water component, is complicated to perform because the water produced in respiration should be also measured. For practical purposes, one can consider that water only transfers to straw through adsorption [8], taking into account that relative humidity in the air is between 88 and 96%. The quantity of water transferred can be calculated with (11):

$$1/M_{wt} \cdot dM_w/dt = (K_a \cdot A \cdot L \cdot (1 - \varepsilon) \cdot s_p) / \nu_p \cdot (C_a - C_p) \quad (11)$$

where M_w is the weight of water (kg); M_{wt} - molecular weight of water, $18kg/kmol$; K_a - adsorption coefficient, m/s ; A -cross sectional area, m^2 ; L -length of bed, m; ν_p -particle mean volume, m^3 ; s_p -particle mean surface area, m^2 ; C_a - concentration of water in the air, $kmol/m^3$; C_p - concentration of water at the particle surface, $kmol/m^3$.

The mass transfer coefficient can be calculated from the Sherwood number definition. Sherwood number is correlated with Reynolds (Re) and Schmidt (Sc) numbers (12):

$$Sh = 2 + 0.6 Re^{1/2} Sc^{1/3} \quad (12)$$

The equation (11) can be used to calculate the total consumption of water during a growth cycle, by integrating this equation for the gradient concentration which varies in time with the variation of the relative humidity in the air.

3. Experimental

Previously, the substrate (wheat straw) had been finely chopped, composted with poultry manure and gypsum and pasteurized. Then it was inoculated with *Pleurotus ostreatus* spawn on millet seeds commercially available. The spawn was spread on successive layers of straw (5-7 cm thick) the top layer being 5-7 cm below the mouth of the bag. A quantity of 2-3 kg spawn for 100 kg is recommended [1,3] but for this study this quantity was decreased to 1.5 kg/100 kg straw due to the higher incubation temperature (25 °C) comparing with the usual 21-22 °C. Plastic bags measuring 18x 25 cm or 20x30 cm are usually used as mushroom beds. There is also an alternative to use high columns of polyethylene instead of bags but the specialists recommend diameters less than 30 cm in any case, to avoid overheating in the middle of the bag. However, we increased slightly the diameter of the straw layer to 40 cm, since the height was 60 cm. Also, the bags have to be placed at some distance from each other in order to allow cooling. Scaling up the process means to have a higher density of bags in the shed, as seen in Figure 1, but this density is limited by the overheating risk.

The bags were placed in a temperature controlled room. The temperature is controlled either with steam (for heating) or with evaporating water (for cooling). Two of the bags were provided with temperature probes ($\pm 0.1^\circ\text{C}$) placed in the middle of the straw layer, in order to measure the temperature during the mycelium growth. The controlled room had also a recording system (on PC) of the humidity, N_2 , O_2 and CO_2 in the air, besides of the wet bulb and dry bulb temperature. The bags were weighed at the start, during the process and in the end. Also, the moisture of the straw was checked in the same time, in order to record variations for the mass transfer purposes.

The mean size of the straw particles was measured by screening samples of straw with a 4 mesh screen then with a 6 mesh screen. Following the screening, three fractions were obtained: fraction I (remaining in the 4 mesh screen), fraction II (passing through the 4 mesh screen but remaining in the 6 mesh screen) and fraction III (passing through the 6 mesh screen). From each fraction, approx.150 straw particles were measured, for the determination of the mean volume and surface of the particles.

4. Results and Discussion

The properties of the straw determined experimentally, with only the thermal capacity taken from literature [4]. These are listed in Table 1. For air properties, comprehensive data can be found in [9].

Using measurements of temperature in the straw bed

for two bags (A, B) as well as in the air, the driving force of the heat transfer (the temperature difference) was calculated; the results are shown in Fig. 2.

TABLE 1. The properties of the straw

Characteristic	Symbol	Unit	Value
Bed density	ρ	kg/m^3	267
Straw density	ρ_s	kg/m^3	900
Bed porosity	ε	-	0.704
Straw initial moisture	H	%	78.8
Straw fractions:			
Fraction I		% wt.	73
Fraction II		% wt.	16
Fraction III		% wt.	11
Mean particle volume	v_p	m^3	$0.106 \cdot 10^{-6}$
Mean particle surface	s_p	m^2	$2.5 \cdot 10^{-4}$

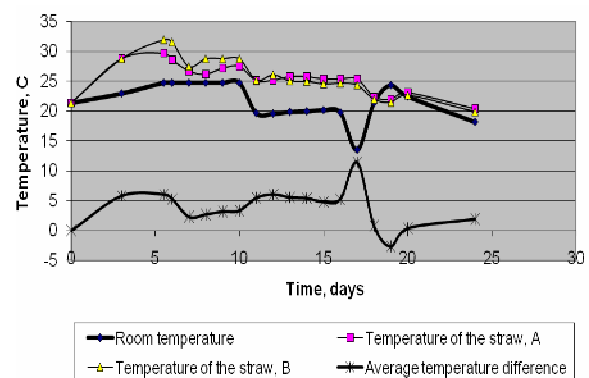


Figure 2. The straw and air temperatures during the test

By measuring the relative air humidity and the moisture in the substrate (straw), the driving force of the mass transfer can be calculated after transforming these in kmol/m^3 . The results of the measurements are shown in Fig.3.

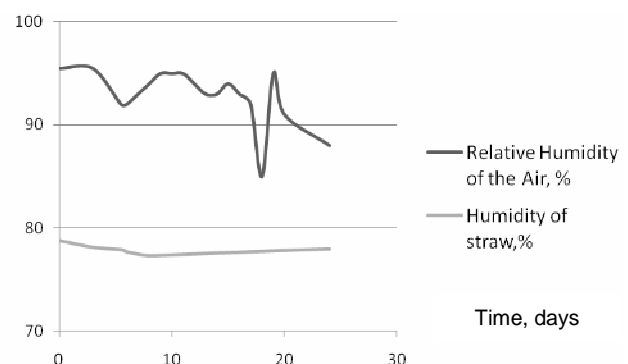


Figure 3. The straw moisture and the relative humidity of the air during the test

Using the equations (1)-(9) and also the definition correlations, the various similitude criteria and thermal transfer coefficient were calculated, as seen in Table 2.

From the Table 2 data, one can notice that the Biot number is 1.90 which indicates the non-uniformity of the temperature in the straw bed.

TABLE 2. The thermal transfer coefficients and similitude criteria

Constant	Symbol	Unit	Value
Effective thermal conductivity (eq.4)	k_b	W/mK	12.56
Rayleigh number (eq. 8)	Ra	-	4595
Nusselt number (eq.7)	Nu	-	4.44
Convective heat coefficient (from Nu definition)	h	W/m ² K	278
Overall heat transfer coefficient	K_o	W/m ² K	51.22
Biot number (eq.1)	Bi	-	1.9

The total heat flux calculated for a body (a straw bag) was 141.6 W, meaning cca. 7.08 W/kg processed straw. For a shed processing 1 ton in a batch, the heat production rate H is then 7.08 kW. Part of this heat is removed naturally, by dissipation through walls. Taking into account the recommended value for the apparent thermal conductivity, the loss of heat through walls depends mainly on the temperature difference between the inner shed and the environment. This can be as much as 1.28 KW for a difference of 20°C. By performing the heat balance (10), the heat remained to be removed by the evaporation of the water can be calculated.

The similitude criteria and mass transfer coefficients calculated with physical constant from [10], are presented in Table 3.

TABLE 3 The similitude criteria for the mass transfer and mass transfer coefficient

Constant	Symbol	Unit	Value
Reynolds number	Re	-	0.017
Schmidt number	Sc	-	0.595
Sherwood number	Sh	-	2.07
Mass transfer coefficient	K_a	m/s	0.0219

The small values of Re and Sh indicates that the air is rather stationary in the shed.

Integrating the equation (11) by taking into account the variation of the humidity in the air and in the straw (Fig.3), the total consumption of water during a growth cycle was calculated and was 65.5 kg/t straw.

5. Conclusions

The present study checked if the growth of *Pleurotus ostreatus* on wheat straw can be scaled-up by increasing the quantity of straw processed in a batch.

The experiment confirmed that increasing the bags diameter to 40 cm can be made without overheating given that the room temperature is maximum 25°C. Until now, the maximum recommended size was 30 cm diameter.

The heat balance performed for the quantity available in this experiment allowed us to calculate the heat production rate which can be used in scaling up the process. This is useful for calculating the evaporative cooling devices.

Mass transfer calculations had as a result the determination of the external spraying of water during a growth cycle.

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