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Heat and Mass Transfer Local Modelling Applied to Biomass Briquette Drying

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Abstract

Biomass is an important source for energy production but remains a high moisture content material. A drying process can increase its energy value. To study the heat and mass transfer in a porous medium, the modelling approach is conducted in order to simulate the drying process of a donut made of compacted biomass. The conservation equation, the transfer laws, the equilibrium equations and the equations of states are established for the three phases of the porous medium: solid, liquid, gas. The finite volume approach is chosen to have access of local and averaged values of temperature and moisture content in particular. The external drying conditions are taken constant for both temperature and relative humidity. The typical shape of donut produced in South Africa is simulated. The temperature evolution is quite rapid (a few hours) while it take several days for the moisture content to reach steady states conditions.

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Keywords: Finite volume method, modelling, drying, biomass, local and global

Nomenclature

C_v	Specific heat capacity, $J.kg^{-1}.K^{-1}$	dt	Step time, s
m	Mass, kg	$\dot{m}$	Mass flow rate, $kg.s^{-1}$
dt	Step time, s	X	Moisture content

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U	Internal energy, J	M	Molar mass, kg.mol^{-1}
S	Surface, m^2	D	Diffusion coefficient, m^2.s^{-1}
c	Molar concentration, mol.m^{-3}	$\dot{Q}$	Heat flux, W
α_h	External heat coefficient, W.m^{-2}.K^{-1}	D_{ext}	External diameter, m
D_{int}	Internal diameter, m	V_{ext}	External Volume, m^3
α_m	External mass flux coefficient, m.s^{-1}	h	Specific enthalpy, J.kg-1
L_v	Latent heat of evaporation, J.kg^{-1}	*Subscripts*	
T	Température, K^{-1}	*vap*	Water vapour
λ	Heat conductivity, W.m^{-1}.K^{-1}	*da*	Dry air
dz	Thickness, m	*liq*	Liquid
dr	Width, m	*evap*	Evaporation

1. Introduction

Over the past few decades, the combination of a number of issues has meant that developing sustainable and renewable energy sources and improving the efficiency of systems using thermal energy, have become increasingly important. Among the possible solutions, using biomass as a fuel is now relatively widespread in the world. The term biomass refers to both energy crops (plants grown specifically to be used as a fuel) and wastes/by-products, such as forestry residues, sawdust and a range of other agricultural wastes, which can all be utilized for energy production in much the same way as coal. Generally, this kind of biomass is a high moisture content material often over 50 % in weight (depending on the type of biomass and climate conditions), which leads to poor energy production for direct use by combustion. One way to valorize it is to carry out a drying process to remove the water from the product by mean of a heat source before any use. An initially low level of fuel moisture however could recover much of the energy used during combustion for water evaporation. Typical lower heating values of dry biomass fuels are ranging between 10 to 20 MJ/kg [1], [2], while coal is about 25, oil 40 and gas 50 MJ/kg. Nevertheless, drying biomass is an energy-intensive process and can easily account for up to 15% of industrial energy utilization. In 2016, La Réunion (an overseas French island situated in the Indian ocean close to Mauritius) produced 241.1 GWh, representing 8.3% of the electricity mix from local biomass, mainly bagasse, a waste from sugar cane production. In South Africa, or more widely in sub-Saharan countries, the local biomass is used by rural communities for cooking or heating. The biomass is locally available from different sources such as agricultural waste, forest residue and green wastes [3], [4]. The knowledge of heat and mass transfer inside the material when dried, is one of the key for their development. A specific shape called donut has been investigated hereafter. In a first part is presented the model being developed when the drying process occurs inside the sample. A finite volume approach is used [5], [6], considering mass and energy balances, thermodynamic equilibrium (liquid/vapor and solid/vapor) and equations of state[7], [8]. In a second part the results obtained from simulation in terms of temperature and moisture content over time are presented.

2. Modelling

The drying process of biomass is complex and involves heat and mass transfer in a heterogeneous, porous and non-isotropic medium. To understand this process, a wide range of modelling approaches has been developed in the recent past [6], [9], [7]. The proper approach depends on the scale and on the physics phenomena to be studied [10]. At a macroscopic scale, it can be assumed that the sample possesses an average temperature and moisture content. This global approach limits the number of equations to solve and decreases the required computational time [11]. However, it does not take into account the internal heat and mass transfer. Thus, a local modelling approach gives important information to better understand the complete behavior of the drying process. Among them, the Whitaker's approach [6], is widely used in the literature [8], [12]–[15]. It gives a set of equations for the drying of a porous media, for a wide range of conditions, relevant for a Representative Elementary Volume (REV). Integrating this set of equations in elementary elements allows the determination of the three variables (temperature, moisture content and relative humidity), that represent the coupling between the biomass sample and the air it is in contact with [7].

This sample being studied (figure 1.a.), is a hollowed cylinder also called donut used in South Africa [3], [4], and submitted to an external air flow. This medium is considered here as homogeneous and isotropic and is composed of three phases: solid, liquid and gas (figure 1.b). The last phase is separated in two species: dry air and water vapor. Due to its relative compactness, only mass diffusion has been considered in the donut and the external air flow does not pass through the biomass and has only an influence on boundaries. A finite volume approach [5] has been chosen in this study to model the drying of compacted biomass and the conservation equations, the transfer laws, the equilibrium between phases and the states equations have been established for each volume.

Fig. 1. (a) biomass sample; (b) schematic view.

The problem being axi-symetric, it becomes 2D and only the radius and thickness are discretized (figure 2.a). Each volume is geometrically characterized by its width (dr) and its thickness (dz). The central and adjacent volumes have common surfaces (north, south, east and west), where the flux are evaluated. The representative point is taken at the mass center of the volume (Figure 2.b).

Fig. 2. (a) donut discretized; (b) central volume

For each volume, the mass conservation equations are given in Table 1:

Table 1. Mass conservation equations

Liquid	Water vapor	Dry air
$\frac{dm_{liq}}{dt} = m_{wood}\frac{dX}{dt} = -\dot{m}_{evap}$	$\frac{dm_{vap}}{dt} = \sum_{N,S,E,W} \pm\dot{m}_{vap} + \dot{m}_{evap}$	$\frac{dm_{as}}{dt} = \sum_{N,S,E,W} \pm\dot{m}_{da}$

The first equation of Table 1 shows the conservation of liquid determined by the moisture content (X) taken on the dry basis. The second equation gives the conservation of the water vapor taking into account the diffusion of vapor through the boundaries and the source terms due to evaporation. Finally, variation of dry air, represented by the third equation, is only due to diffusion through the boundaries of the domain. The energy conservation equation is given by neglecting the kinetics and potential energy, the compressional work and viscous dissipation [16]. It is considered that the system is in local thermal equilibrium [14] (all phases have the same temperature) and thus the energy conservation is given by:

$$\frac{dU}{dt} = \sum_{N,S,E,W} (\pm\dot{m}_{vap}.h_{vap} \pm \dot{m}_{da}.h_{da}) + \sum_{N,S,E,W} \dot{Q} - L_v.\dot{m}_{evap} \tag{1}$$

Where U is the internal energy whose variation is due to the transport of energy by diffusion of water vapor and dry air, the net flux by heat conduction in the solid phase and the source flux due to the evaporation. The diffusion fluxes given above are governed by Fick's law [17], [18] and Fourier's law [19], [20]. Their expressions are summarized in Table 2:

Table 2. Transfer equations

Mass Flux	Heat flux
$\dot{m}_i = -\mathrm{M}_i.S.D.\nabla c_i \;\big\|_{i\,=\,vap,da}$	$\dot{Q} = -\lambda.S.\nabla T$

The first equation represent the mass flow of water vapor or dry air passing through the domain due to the gradient of molar concentration. The second equation is the heat flux due to temperature difference. For both fluxes, apparent or equivalent values for conductivity and diffusivity have been chosen in our case. Their numerical values will be taken later from the literature. The liquid phase is considered as incompressible. The gaseous phase is composed of water vapor and dry air and is represented by an ideal mixture of ideal gases. The liquid/vapor equilibrium of water is given by the saturation equation [21] and the solid/vapor equilibrium is given by Simpson's sorption isotherm [22], [23]. Finally, the boundary conditions are taken for heat and mass transfer with constant coefficients, respectively α_h and α_m as given in Table 3. Subscript *surf* stands for external area of the sample and *ext* for external conditions.

Table 3. Boundary conditions

Heat	Mass
$\dot{Q} = \alpha_h.S.\left(T_{surf} - T_{ext}\right)$	$\dot{m}_i = M_i.\alpha_m.S.\left(c_{surf} - c_{ext}\right) \;\big\|_{i\,=\,vap,da}$

Solving this set of equations is done thanks to an RK4 explicit method and allows accessing to the three representative variable *i.e.* temperature, moisture content and relative humidity for each volume.

3. Simulation and results

The simulation is done considering the shape of the donut generally used in South Africa (figure 1.a) with a height of 0.07 m, an internal diameter of 0.025 m and an external diameter of 0.1 m. The corresponding volume as fulfilled with wood chips leading to a dry mass of 155 g. The results are graphically represented in terms of temperature rise and moisture content decrease for six different locations (see figure 2.a) situated inside the donut. The averaged values, calculated over the whole domain following the definitions given in table 4, are also represented. Due to the symmetry of the studied case, only the half of the donut is represented.

Table 4. Integrated values

Average Moisture Content	Average Temperature
$\overline{X} = \dfrac{\sum m_{liq}}{\sum m_{wood}}$	$\overline{T} = \dfrac{\sum U}{\sum(\mathrm{Cv}_{\mathrm{wood}}.\mathrm{m}_{\mathrm{wood}} + \mathrm{Cv}_{\mathrm{liq}}.\mathrm{m}_{\mathrm{liq}})}$

At initial conditions, the sample is surrounded by air at a temperature of 20°C and a relative humidity of 60 %, leading to an initial moisture content of the biomass sample of approximately 11% given by the Simpson sorption equation. The drying process starts when the air outside the donut is heated up to 50°C, keeping the same amount of water in the air. The samples properties are taken from the literature: a value of 0.14 $W.m^{-1}.K^{-1}$ is chosen for the heat conductivity [12], 500 $kg.m^{-3}$ for the dry density [8] and 1500 $J.kg^{-1}.K^{-1}$ for the heat capacity of the solid phase [8]. The diffusion coefficient for water vapor and dry air is 6.10^{-7} $m^2.s^{-1}$ [8] and the porosity is 0.6 [24]. Finally, for boundary conditions, the heat and mass flux coefficient are taken also from the literature, respectively 25 $W.m^{-2}.K^{-1}$ [11] and to $2.5.10^{-2}$ $m.s^{-1}$ [11].

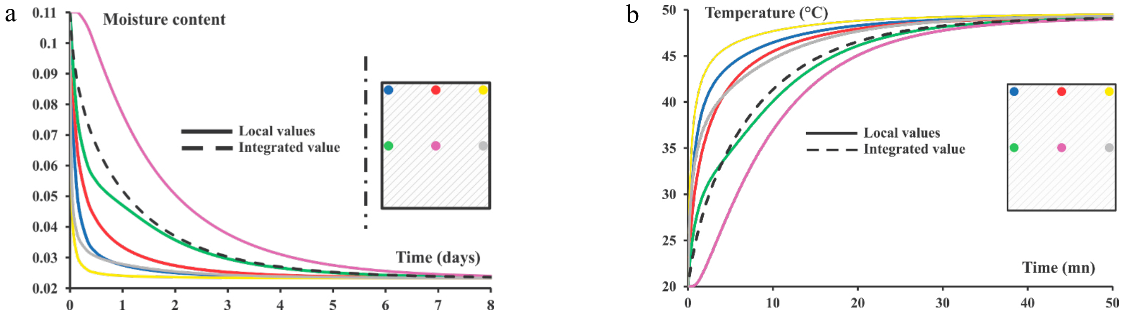

Fig. 3. (a) Moisture content and (b) temperature of the sample over time.

The drying simulating takes about 8 days and Figure 3.a, shows the moisture content decrease as well as an important difference of behavior depending on volume position. At the beginning, the variation is important for external volumes (blue, red, yellow, green and grey) due to the proximity of the exchange area and to the high gradient between dry air and wet biomass conditions. On the contrary, the internal volume situated approximately in the center of the sample (purple) benefits from a certain delay before being affected by the change of external conditions. It's due to the time required by the drying front to reach the internal volumes. The rise of temperature (Figure 3.b) is much faster than the moisture extraction: in less than 1h, the temperature of the whole sample reaches the external temperature of 50°C. A light difference of temperature still exists between the air and the sample due to internal evaporation which tends to cool the biomass. Figure 4 shows the temperature profile inside the donut at different step time (1, 5, 10 and 15 mn), illustrating the rapidity of heat transfer in this case. On the contrary, the humidity transfer is much slower as seen in the figure 3 and also in figure 5 where is represented the moisture content inside the sample for different step time (1, 2, 3 and 4 days). Apparently, considering the parameters used in this simulation and mainly coming from the literature, the global behavior is principally driven by mass transfer.

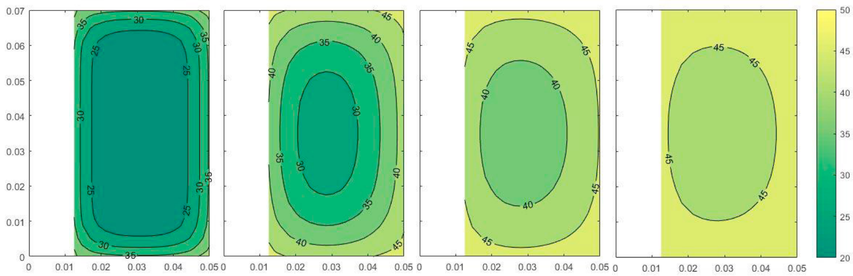
Fig. 4. Temperature profile in the donut at different step time: 1 mn, 5 mn, 10 mn, 15 mn.

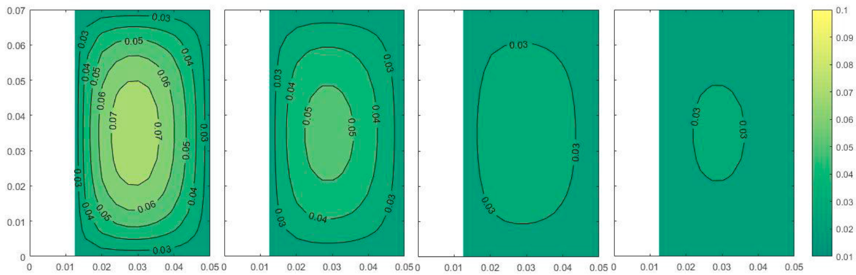
Fig.5. Moisture content in the donut at different step time: 1 day, 2 days, 3 days, 4 days.

4. Conclusion and perspectives

The study focused on the modelling of the drying of biomass briquettes under constant temperature and humidity. These briquettes have the shape of donuts, i.e. cylinder with a central hole. A set of equations has been presented for the three phases present in the porous medium *i.e.* solid, liquid and gas. The model takes into account the heat conduction, the liquid evaporation and the gas diffusion of species (dry air and water vapor) inside the medium. The whole has been integrated using the finite volume approach for a two dimensional model (thickness and radius). Simulation show an important difference of behavior between central and peripheral positions in the sample. In about an hour, almost the whole sample has reached the external temperature conditions, demonstrating the fact that in this case, the limiting effect is not heat transfer. On the contrary, drying the sample so as to reach steady states conditions requires à few days mainly because of the internal moisture diffusion. In future works, others shapes of donut will be test to study the influence of the size on the global results with a constant volume of matter.

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