ANALYSIS OF PARAMETERS IMPORTANT FOR INDIRECT DRYING OF BIOMASS FUEL

Michel Sabatini*, Jan Havlík, Tomáš Dlouhý

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Energy Engineering, Technická 4, 166 07 Prague 6, Czech Republic

* corresponding author: michel.sabatini@fs.cvut.cz

Abstract. This paper focuses on biomass drying for the design and operation of an indirect dryer used in a biomass power plant. Indirect biomass drying is not as well described process as direct drying, especially when used for the preparation of biomass in energy processes, such as combustion or gasification. Therefore, it is necessary to choose a suitable model describing the drying process and evaluate its applicability for this purpose. The aim of this paper is to identify parameters that most significantly affect the indirect drying process of biomass for precise targeting of future experiments. For this purpose, the penetration model was chosen. The penetration model describes indirect drying through 21 parameters. To run a series of experiments focused on all parameters would be time consuming. Therefore, the easier way is to select the most important parameters through a sensitivity analysis, and then perform experiments focused only on the significant parameters The parameters evaluated as significant are the temperature of the heated wall, operating pressure in the drying chamber, surface coverage factor, emissivity of the heated wall, emissivity of the bed, diameter of the particle, and particle surface roughness. Due to the presumption of perfect mixing of the material being dried, stirrer speed is added into important parameters. Based on these findings, it will be possible to reduce the scope of experiments necessary to verify the applicability of the penetration model for the description of indirect biomass drying and the design of dryers for a practical use.

Keywords: Contact drying, indirect drying, penetration model, drying rate.

1. Introduction

Biomass as an energy source is an important component of the energy mix with respect to the departure from coal combustion and the established trend of using renewable energy sources. However, many kinds of biomass, e.g., wood chips, bark, or some agricultural residues, have a high moisture content that affects their energy use. The energy consumption for drying the biomass is significant. Therefore, it is important to dry biomass with the lowest possible energy intensity.

Biomass drying for power generation is commonly done in convective dryers, which are less energy-effective than indirect dryers. Therefore, replacing a convective dryer with an indirect dryer should result in energy savings. The difference between indirect (contact, conductive) and convective dryers is in the way how the heating medium supplies its heat to the material. In the case of direct dryers, the material being dried comes into a direct contact with the flow of the heating medium, which is most often air or flue gas. In the case of indirect dryers, a heating medium does not come into contact with the material being dried and the heat is transferred to the material through a heated wall of the dryer [1].

Indirect dryers are more energy effective because a lesser heat loss in the heating medium can be achieved. Moreover, any form of heat (e.g. waste heat) can be used for drying, which is particularly noticeable when using steam heating. In addition, the heat in water vapour produced during the drying can be recovered, for example, in the previous operation for pre-drying, and reduce the overall energy consumption of drying. The average energy consumption of indirect dryers is reported to be in the range of 2800–3600 kJ/kg while direct dryer's consumption is in the range of 4000–6000 kJ/kg [2, 3].

Many papers have been written on the subject of indirect drying for very specific materials and dryers. Based on these papers, there are two main models used for a description of indirect drying. The first of them is based on simultaneous heat, mass and momentum transfer in porous media given by Whitaker in [4, 5]. This model was used to investigate pharmaceutical materials dried in a laboratory vacuum dryer or in the Nutsche filter dryer in [6–11]. The second model is called the penetration model, the heat transfer of this model was described in [12] and then extended to be applicable for indirect drying in a pure vapour atmosphere in [13]. The following authors improved the penetration model for both the specific properties of the material and the specific drying conditions: for multigranular beds [14], for materials with hygroscopic behaviour [15–17], for granular beds wetted with a binary mixture [18], for indirect drying in the presence of an inert gas [17, 19]. In the paper [20], authors were taking into account the local kinetics of grain dehydration or the diffusion of vapour inside the bed to improve the model. Most of the previous
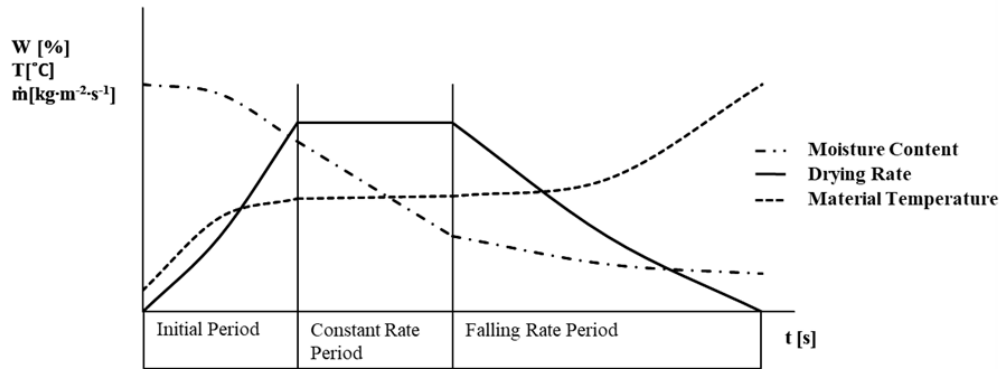
FIGURE 1. Schematic illustration of moisture content, drying rate, and material temperature.

articles were focused on the materials with a spherical shape. There are few other studies focused on different materials. Paste materials dried in LIST-type kneader dryer were examined in [21]. Drying of sewage sludge was studied in [22, 23]. Crystalline powders were the focus of studies [24, 25], and other types of powders in [26]. A comparison of the penetration model with the discrete modelling was done in [27]. Recent articles on indirect drying of biomass can be found in [28–30].

None of these studies aimed to describe the drying of biomass fuel in an indirect dryer using the penetration model. The novelty of the research is the modification and subsequent use of this model, because the model is derived and verified for materials with uniform shape and size and for conditions that are different from biomass, which has very inhomogeneous physical properties. The aim of this paper is to analyse the theoretical description of the biomass indirect drying process and to evaluate its applicability in the design of an indirect dryer for a biomass power plant. For a theoretical description of the indirect drying process, the penetration model can be used. To experimentally verify the model for the material and conditions corresponding to indirect drying of biomass, due to the large number of parameters that can influence the drying, many experiments would have to be done to determine the impact of each parameter on the drying process. Therefore, reducing the number of necessary experiments, through the sensitivity analysis of the drying process to changes in individual parameters was evaluated using the penetration model. The parameters with the greatest influence on the process were determined.

2. Materials and methods

2.1. Drying kinetics

The drying process consists of three main periods shown in Figure 1. In the initial period, both the temperature of the material and the drying rate rise rapidly. For the second period, a constant drying rate is typical. The temperature of the material rises very slowly and the moisture content decreases linearly. In the third period, the drying rate steadily decreases and the temperature of the material begins to increase fast. Biomass, as fuel, is usually being dried from a high moisture content to the level optimal for combustion, which is around $0.4 \, \mathrm{kg_w \, kg_{dry}^{-1}}$. Drying of fuel takes place primarily in the initial and constant rate period. The initial period is usually short compared to the constant rate period, and it can be neglected. Moisture content is defined by equation (1).

$$X = \frac{m_w}{m_{dry}}, \tag{1}$$

where m_w [kg] is the weight of water and m_{dry} [kg] is the weight of dry matter.

2.2. Specifics of biomass fuel drying

Typical types of waste biomass used for a combustion are fresh wood chips and bark. Drying of wood chips or bark has some specifics. The material is usually very moist, the optimal target remaining moisture content after drying is about $0.4 \, \mathrm{kg_w \, kg_{dry}^{-1}}$. Therefore, drying mostly takes place in the constant drying rate period. In this period, some of the parameters from the penetration model do not significantly affect its results, their influence increases only in the falling rate period. The identification of these negligible parameters can be done by a sensitivity analysis. Excluding them will reduce the scope of experiments required for the verification of the penetration model and evaluate its applicability for the description of contact drying of biomass.

2.3. Penetration model

The penetration model describes the heat and mass transfer during indirect drying. Thus, for specific conditions of the drying process, it is possible to theoretically calculate the heat transfer coefficient between the heated surface of the dryer and the material being dried, and subsequently determine the drying rate. The drying model was proposed by Schlünder and Mollekopf in [13]. The model is developed for drying mechanically agitated particulate materials in a pure

vapour atmosphere. The steady mixing process is substituted by a sequence of steps in which the material is stagnant for a fictitious period of time t_R and at the end of this period, the material is instantaneously and perfectly mixed. In the rest of the chapter, the model is briefly explained. A detailed explanation of the model can be found in the listed citation [12, 13]. The contact heat transfer coefficient can be calculated according to Schlünder [12]:

$$\alpha_{WS} = \varphi\alpha_{WP} + \alpha_{rad}, \tag{2}$$

where φ is the surface coverage factor (the heated surface which is in direct contact with the material), α_{WP} is the wall-particle heat transfer coefficient, α_{rad} is the heat transfer coefficient by radiation.

$$\alpha_{WP} = \frac{4\lambda_g}{d_{equiv}}\left[\left(1 + \frac{2(l+\delta)}{d_{equiv}}\right) \cdot \ln\left(1 + \frac{d_{equiv}}{2(l+\delta)}\right) - 1\right], \tag{3}$$

where d_{equiv} [m] is the equivalent diameter of the particle:

$$d_{equiv} = \sqrt[3]{\frac{6V}{\pi}}, \tag{4}$$

where V [m³] is the volume of the particle, λ_g is the thermal conductivity of the gas, and δ is the roughness of the particle surface.

$$\alpha_{rad} = 4 \cdot C_{W,bed} \cdot T^3, \tag{5}$$

where T is the mean temperature, and $C_{W,bed}$ is the overall radiation coefficient calculated by:

$$C_{W,bed} = \frac{\sigma}{\left(\frac{1}{\varepsilon_W} + \frac{1}{\varepsilon_{bed}} - 1\right)}, \tag{6}$$

where σ is the Stefan–Boltzmann constant, ε_W is the emissivity of the heated wall, and ε_{bed} is the emissivity of the bed.

The modified mean free path of the gas molecules l is defined as follows:

$$l = 2 \cdot \frac{2-\gamma}{\gamma}\sqrt{\frac{2\pi\tilde{R}T}{\tilde{M}}}\frac{\lambda_g}{p\left(2c_{p,g} - \frac{\tilde{R}}{\tilde{M}}\right)}, \tag{7}$$

where γ is the accommodation coefficient, $\tilde{R}$ is the ideal gas constant, $\tilde{M}$ is the molecular weight of the gas, p is the operating pressure, and $c_{p,g}$ is the specific heat of the gas.

The penetration heat transfer coefficient of a dry bed can be expressed as:

$$\alpha_{bed,dry} = \frac{2}{\sqrt{\pi}}\frac{\sqrt{(p\lambda c)_{bed,dry}}}{\sqrt{t_R}}, \tag{8}$$

and of a wet bed as:

$$\alpha_{bed,wet} = \frac{\alpha_{bed,dry}}{\text{erf}\,\zeta} = \frac{2}{\sqrt{\pi}}\frac{\sqrt{(p\lambda c)_{bed,dry}}}{\sqrt{t_R}}\frac{1}{\text{erf}\,\zeta}, \tag{9}$$

where:

$$t_R = \frac{N_{mix}}{n}, \tag{10}$$

where for a paddle dryer, N_{mix} is calculated:

$$N_{mix} = 9 \cdot Fr^{0.05}, \tag{11}$$

and Fr Froude number obtained from:

$$Fr = \frac{(2\pi n)^2 \cdot D}{2g}, \tag{12}$$

where n is the stirrer speed, D is the diameter of the vessel, and g is the gravitational acceleration.

The reduced instantaneous position of the drying front ζ can be calculated from:

$$\zeta = \frac{z_T}{2\sqrt{\kappa_{bed,dry}t}}, \tag{13}$$

where $\kappa_{bed,dry}$ is the overall thermal diffusivity of the dry bed:

$$\kappa_{bed,dry} = \frac{\lambda_{bed,dry}}{(\rho c)_{bed,dry}}, \tag{14}$$

and ζ is determined from the relationship:

$$\sqrt{\pi} \cdot \zeta \cdot \exp\left(\zeta^2\right)\left[\left(\frac{\alpha_{WS}}{\alpha_{dry}} - 1\right) \cdot \text{erf}\,\zeta + 1\right] = \frac{1}{\xi}\left(\frac{\alpha_{WS}}{\alpha_{dry}} - 1\right), \tag{15}$$

where ξ is the reduced average moisture content of the bed:

$$\xi = \frac{X\Delta h_\nu}{c_{bed,dry} \cdot (T_W - T_{bed})}. \tag{16}$$

The overall heat transfer coefficient of a dry bed can be determined from the relation:

$$\frac{1}{\alpha_{dry}} = \frac{1}{\alpha_{WS}} + \frac{1}{\alpha_{bed,dry}}, \tag{17}$$

and of a wet bed from:

$$\frac{1}{\alpha} = \frac{1}{\alpha_{WS}} + \frac{1}{\alpha_{bed,wet}}. \tag{18}$$

The overall heat transfer coefficient α is expressed as follows:

$$\alpha = \frac{\alpha_{WS}}{1 + \left(\frac{\alpha_{WS}}{\alpha_{dry}} - 1\right) \cdot \text{erf}\,\zeta}. \tag{19}$$

The flux at the hot surface:

$$\dot{q}_0 = \alpha(T_W - T_{bed}), \tag{20}$$

and the heat flux at the drying front:

$$\dot{q}_{lat} = \alpha(T_W - T_{bed}) \cdot \exp\left(-\zeta^2\right) \tag{21}$$

The drying rate is obtained from:

$$\dot{m} = \frac{\dot{q}_{lat}}{\Delta h_\nu}. \tag{22}$$

The results of this step are differences in both the moisture content and the bed temperature (equations (23) and (24)), which serve to determine the new moisture content and the new bed temperature (equations (25) and (26)), which are inputs for the next step.

$$\Delta X = \frac{\dot{m} t_R A}{m_{dry}}, \qquad (23)$$

where A is the covered surface of the heating wall depending mainly on the geometry of the dryer and the filling ratio.

$$\Delta T_{bed} = \Delta X \frac{\Delta h_\nu}{c_{bed,dry} + c_L X} \cdot [\exp /\zeta^2) - 1], \quad (24)$$

$$X_{i+1} = X_i + \Delta X_i, \qquad (25)$$

$$T_{bed,i+1} = T_{bed,i} + \Delta T_{bed,i}. \qquad (26)$$

The penetration model allows us to calculate the drying rate and the heat transfer coefficient, which are the main parameters needed for the design of an indirect dryer. Furthermore, the penetration model can predict the temperature of the material, which is important for drying temperature-sensitive materials.

2.4. Sensitivity analysis using penetration model for indirect drying of biomass

The aim of the sensitivity analysis of the penetration model is to determine the effect of the change in the v of individual input parameters on its overall heat transfer coefficient and drying rate. A large number of parameters enter into the calculation. For a practical use, under specific conditions, these parameters must be determined experimentally, often by very complex methods. Therefore, it is desirable to select parameters whose change has little effect on the results of the model, and their value can be determined in a simplified way or by estimation. High-sensitivity parameters can cause large variations in results even with a small change, so great care must be taken to determine their exact value. Based on the conclusions of the sensitivity analysis, it is possible to propose a precise plan for experiments for the model validation.

All parameters used in the penetration model for drying in a pure steam atmosphere were identified. In general, these parameters can be divided into three basic categories that describe the properties of the material, evaporated substance, and equipment.

Material properties: bed temperature, dry bed density, dry bed thermal conductivity, dry bed specific heat capacity, diameter of the particle, surface roughness of particles, bed emissivity, and moisture content.

Properties of evaporated substance: thermal conductivity, molar mass, operating pressure, specific heat capacity, latent heat, and accommodation coefficient.

Equipment properties: heated wall temperature, heated wall emissivity, surface coverage factor, stirrer speed, dryer diameter, and constants C and x.

Selection of analysed parameters: Some of the above parameters are defined for a specific material or device and usually cannot be changed, or their change depends on a change of other parameters, such as temperature or operating pressure. These parameters include the density of the dry bed of material, thermal conductivity of the dry bed, specific heat capacity of the dry bed, surface roughness of particles, thermal conductivity of the evaporated substance, molar mass of the evaporated substance, specific heat capacity of the evaporated substance and accommodation coefficient, emissivity of the heated wall, emissivity of the bed, surface coverage factor, diameter and length of the vessel, and moisture content. The moisture content of the material is usually specified and for this reason, it is also considered as an input parameter that cannot be changed. The parameters of the evaporated substance (in this case water) are determined from the steam tables.

However, the temperature of the heated wall, stirrer speed, operating pressure (if vacuum drying is applied), and associated temperature of the bed, and in some cases, also the diameter of the particle can be changed within a certain range according to the technological requirements. The constants C and x were determined by the authors of the model, and they are empirically determined parameters, for the purpose of this analysis, they are considered constant. However, the literature review showed that even these values are modified by some authors for more accurate results and therefore, it is possible to adjust them for specific equipment and materials [22].

Although it is not possible to change some of the parameters of the model, it is important to identify their influence and thus the importance of their exact determination. These parameters include the density of the dry bed, thermal conductivity of the dry bed, specific heat capacity of the dry bed, surface roughness of particles, emissivities of the heated wall and bed, surface coverage factor, and accommodation coefficient.

The sensitivity analysis is performed for the expected reference value of the parameter, and its value is usually changed in the range of $\pm 50\,\%$. In some cases, when an assumed change of a given parameter could make a difference, the range of the analysis is adjusted to cover probable conditions. A value of $100\,\%$ represents the reference case.

2.5. Reference case of indirect drying of biomass

The reference values of the parameters used in the sensitivity analysis are in Table 1. A horizontal paddle dryer is used, and the substance being evaporated is water. The chosen conditions represent both the material and the dryer, which will be used for future experiments and for validating the model for the purpose of biomass fuel drying. The drying of biomass fuel usually takes place under nearly atmospheric con-

Parameter		Unit	Value
diameter of the vessel	D	mm	256
length of the vessel	L	mm	1000
constant C	C	-	9
constant x	x	-	0.05
emissivity of the heated wall	ε_w	-	0.8
temperature of the heated wall	T_w	°C	130
operating pressure	p	bar	1.01325
stirrer speed	n	RPM	17
equivalent particle diameter	d_{equiv}	mm	10
density of the bed	ρ_{bed}	$\mathrm{kg\,m^{-3}}$	450
specific heat capacity of the bed	c_{bed}	$\mathrm{J\,kg^{-1}\,K^{-1}}$	1500
thermal conductivity of the bed	λ_{bed}	$\mathrm{W\,m^{-1}\,K^{-1}}$	0.18
emissivity of the bed	ε_{bed}	-	0.94
moisture content	X_0	$\mathrm{kg_w\,kg_{dry}^{-1}}$	1
accommodation coefficient	γ	-	0.8
surface coverage factor	φ	-	0.3
amount of dry matter	m_{dry}	kg	2.19
surface roughness of particles	δ	µm	500

TABLE 1. Reference case.

ditions. For the purpose of the analysis, drying at a lower pressure was also considered, which would increase the drying rate. Vacuum conditions allow using low-potential waste heat for drying, which would be otherwise lost. The benefit of using waste heat may overcome the energy required to run the vacuum pump.

3. RESULTS AND DISCUSSION

Results of the sensitivity analysis allow us to divide the input parameters of the model into significant and negligible according to how strongly they affect the drying process. The effect of changing the parameter on the size of the heat transfer coefficient from the heated wall to the material being dried and on the drying rate, which are the two most important parameters for the dryer design, was evaluated. The parameter was classified as significant if the change in the heat transfer coefficient or drying rate was greater than 3 % in the analysed range.

Low impact parameters According to Figure 2 and Figure 3, the parameters with little influence on both the heat transfer coefficient and the drying rate are usually material properties, such as the thermal conductivity of the material bed, heat capacity of the material bed, density of the material bed, and the accommodation coefficient, i.e., the parameter related to the properties of the evaporated substance. Changing these parameters has a negligible influence on the result of drying in the constant drying rate period. The last parameter is the stirrer speed, this parameter still needs to be verified experimentally, because one of the assumptions of the model is to achieve perfect mixing of the material, therefore, it is

possible that the allowed speed range will be limited.

Strong impact parameters The following two figures show the strong influence of other parameters on the change of the heat transfer coefficient α and the drying rate. These parameters include temperature, operating pressure, diameter of the particle, emissivity of the heated wall, emissivity of the bed, surface roughness of particles, and surface coverage factor of the dryer. The greater the slope of the curve, the stronger the influence of the parameter. From the graph in Figure 4, it can be seen that the value of the heat transfer coefficient is most influenced by the surface coverage factor, temperature, emissivity, diameter of the particle, and surface roughness of particles. All of these parameters have a similar effect on the heat transfer coefficient. The influence of parameters on the change in drying rate is slightly different. Figure 5 shows the dominant effect of temperature. A smaller effect can be observed for the coverage, emissivity coefficients, and operating pressure. Lowering the pressure has a negative impact on the heat transfer coefficient, but a positive impact on the drying rate. The effect of roughness and particle diameter on the drying rate is weaker.

Overall evaluation The penetration model used to describe the heat transfer coefficient and the drying rate of contact drying works with 21 parameters. Ten of these parameters are related to the type of dryer and the evaporated substance, their value is determined by the specific circumstances of the case and cannot be easily changed. The remaining 11 parameters determine the properties of the material being dried and the conditions of the process that may be
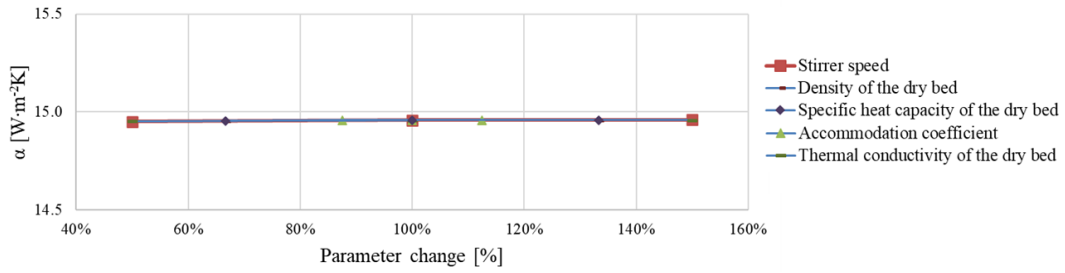
FIGURE 2. Parameters with low impact on the heat transfer coefficient.
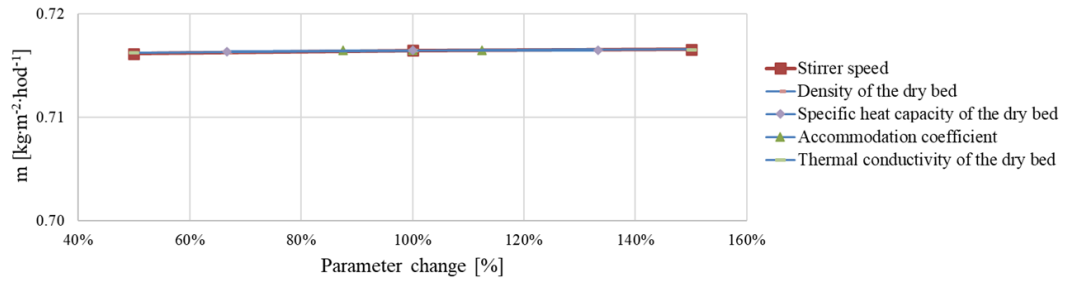

FIGURE 3. Parameters with low impact on the drying rate.
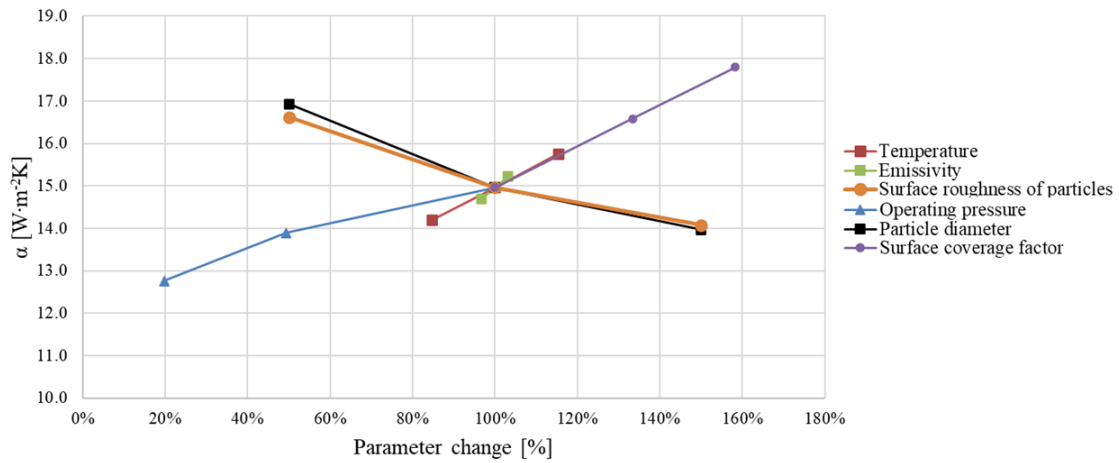

FIGURE 4. Parameters with strong impact on the heat transfer coefficient.
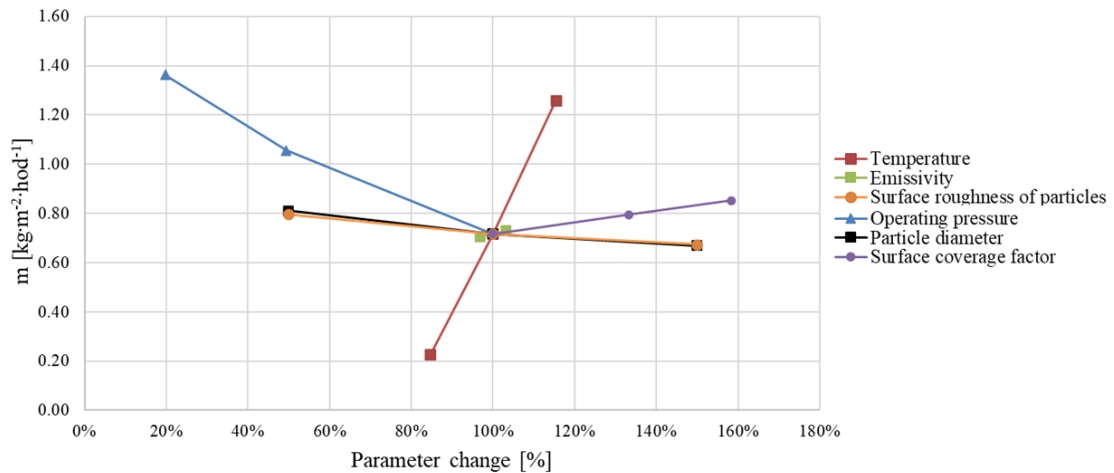

FIGURE 5. Parameters with strong impact on the drying rate.

variable or might be important for the drying. According to the results of the sensitivity analysis, only 7 of these parameters can significantly affect the drying process in the constant drying rate period. These parameters are – temperature of the heated wall, operating pressure, diameter of the particle, and other parameters that are important and it is necessary to determine them accurately. These parameters include the emissivity of the heated wall, emissivity of the bed of the material, surface coverage factor, and surface roughness of the particles. The penetration model assumes perfect mixing of the bed of material, therefore, it is desirable to also include stirrer speed among the important parameters and into a scheme of verification experiments. The influence of stirrer speed will probably be noticeable only at very low speeds.

4. Conclusion

The sensitivity analysis of the penetration model describing the heat transfer process in indirect dryers for the purpose of fuel drying has been done. For the drying process in the constant rate period, the most important parameters were identified. Changing them will be reflected in a significant change in the results of the model. In the case of using the penetration model to design a real biomass dryer, these parameters must be precisely determined within specific ranges that will correspond to the properties of the fuel and the required drying conditions. These parameters are the temperature of the heated wall, operating pressure, surface coverage factor, diameter of the particle, emissivity of the heated wall, emissivity of the bed, and surface roughness of particles. Moreover, it is recommended to include stirrer speed in a set of important parameters, especially at low stirrer speeds.

Future research will focus on the experimental verification of the use of the penetration model to describe the drying of biomass in an indirect dryer in order to validate its applicability for the design of real equipment.

List of symbols

A covered surface of the heating wall $[\mathrm{m}^2]$

C constant $[-]$

c specific heat capacity $[\mathrm{J\,kg^{-1}\,K^{-1}}]$

$C_{W,bed}$ overall radiation coefficient $[-]$

c_p specific heat capacity at constant pressure $[\mathrm{J\,kg^{-1}\,K^{-1}}]$

D diamater of the vessel $[\mathrm{m}]$

d_{equiv} equivalent particle diameter $[\mathrm{m}]$

Fr Froude number $[-]$

g gravitational accelaration $[\mathrm{m\,s^{-2}}]$

Δh_ν latent heat of evaporation $[\mathrm{J\,kg^{-1}}]$

L lenght of the vessel $[\mathrm{m}]$

m weight $[\mathrm{kg}]$

$\dot{m}$ drying rate $[\mathrm{kg\,m^{-2}\,s^{-1}}]$

$\tilde{M}$ molar mass $[\mathrm{kg\,mol^{-1}}]$

n stirrer speed $[\mathrm{RPM}]$

N_{mix} mixing number $[-]$

p operating pressure $[\mathrm{Pa}]$

$\dot{q}$ heat flux $[\mathrm{W\,m^{-2}}]$

$\tilde{R}$ universal gas constant $[\mathrm{J\,mol^{-1}\,K^{-1}}]$

T temperature $[\mathrm{K}]$

t_R contact time $[\mathrm{s}]$

V volume of the particle $[\mathrm{m}^3]$

X moisture content $[\mathrm{kg_w\,kg_d^{-1}ry}]$

x constant $[-]$

z_T position of the drying front $[\mathrm{m}]$

Greek symbols

α heat transfer coefficient $[\mathrm{W\,m^{-2}\,K^{-1}}]$

γ accommodation coefficient $[-]$

δ surface roughness of particles $[\mathrm{m}]$

ϵ emissivity $[-]$

ζ dimensionless position of phase change front $[-]$

l modified mean free path of gas molecules $[\mathrm{m}]$

κ thermal diffusivity $[\mathrm{m^2\,s^{-1}}]$

λ thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$

ξ reduced average moisture content $[-]$

ρ density $[\mathrm{kg\,m^{-3}}]$

σ Stefan-Boltzmann constant $[\mathrm{W\,m^{-2}\,K^{-4}}]$

φ surface coverage factor $[-]$

Subscripts

$_0$ initial

$_{bed}$ bed of the material

$_{dry}$ dry matter

$_g$ gas

$_L$ liquid

$_{rad}$ radiation

$_W$ heated wall

$_w$ water

$_{wet}$ wet matter

$_{WP}$ wall-particle

$_{WS}$ contact

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