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Implementation of the first period of convective drying in a commercially available CFD package

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Abstract

The issue of the drying of woodchips is investigated in this paper. The most widespread type of the solid drying is a packed bed convective drying process with hot air as a working medium that is considered here. A comprehensive survey has proven a severe shortage of 3D drying-oriented computational fluid dynamics (CDF) packages for handling packed beds. This work was carried out by means of User Defined Procedures (UDF) – self written codes in C implemented in a commercially available CFD package – Ansys Fluent. A strongly flattened fixed bed of woodchips was investigated whose dimensions equaled to 1.5 m×1.5 m×0.2 m in length, width and height, respectively. In theoretical modeling woodchips were assumed as spheres of unique size settled in a cubic layout. The first period of drying was taken into consideration with the inlet air temperature 60 °C and humidity 0%. The temperature of the packed bed was set to the wet bulb temperature 21 °C. The vapor flux was implemented as a source term in the continuity equation. The core part of the UDF was a DEFINE_SOURCE macro that comprised the source term for evaporating water and partially the liquid water storage. As a result the drying air was humidified from initial 0%, to 22% along the bed, at a constant air enthalpy. The air temperature decreased from 60 °C to 38 °C, and the drying rate fell from 0.22 to 0.10 kg/m^{3}s.

Keywords: Through-flow; Drying; CFD; UDF; First period; Woodchips

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Nomenclature

A	–	woodchips' surface area, m^2
A_{fs}	–	interfacial area density, 1/m
D_p	–	mean woodchip diameter of equivalent sphere, m
E_s	–	solid medium energy, J
h	–	heat transfer coefficient, W/m^{2}K, W/m^{3}K
h_s	–	heat transfer at fluid-solid interface, W/m^{2}K
k	–	fluid, air thermal conductivity, W/mK
k_s	–	solid medium thermal conductivity, W/mK
m_d	–	dry wood mass, kg
m_w	–	moisture mass, kg
n	–	number of woddchip particles
p	–	pressure
RH	–	relative humidity
S^h	–	fluid, enthalpy source term, J
S_s^h	–	solid enthalpy source term, J
T	–	fluid, air temperature, $^\circ$C
T_d	–	temperature of dry inlet air, $^\circ$C
T_s	–	temperature of solid, $^\circ$C
t	–	time, s
u	–	air velocity, superficial, m/s
V	–	volume of woodchips, m^3
X	–	moisture content, dry basis, kg/kg
X_c	–	critical moisture, content, kg/kg
X_{eq}	–	equilibrium moisture content, kg/kg
X_1	–	initial moisture content in wood, kg/kg
X_2	–	final moisture content, kg/kg
Y	–	moisture content in air, kg/kg
z	–	flow longitudinal axis, m

Greek symbols

ε	–	porosity
ρ	–	fluid, air density, kg/m^3
ρ_c	–	wood bulk density, kg/m^3
ρ_s	–	density of solid, kg/m^3

Subscripts

c	–	critical, conventional
d	–	dry
fs	–	fluid–solid interface
s	–	solid
w	–	moisture, wet, water

1 Introduction

Drying is a well known on a practical basis chemical process of removing water or other liquid. It covers a wide range of possible systems: liquid–liquid, gas–liquid and liquid–solids. Here only the latter is taken into account. Dryers of solid materials can be classified in three ways. The mode of operation – batch or continuous. The mode of heat transfer – direct-heat (also called convective or adiabatic) or indirect-heat (also called nonadiabatic as the heat is provided by conduction, radiation, etc.). The last way of classification is the degree to which the material is agitated – in some dryers, the feed is stationary while being processed whereas at the opposite extreme is the fluidized-bed dryer. This paper is limited to the considerations of a batch convective heat dryer with woodchips as the dried material and hot air as the drying medium. The layout of the feed is as simple as possible since the main goal of the work is to implement drying mechanisms into computational fluid dynamics (CFD) commercial package [12] – Ansys Fluent. So the packed bed has a form of a strongly flattened cubic. The drying air passes down through the feed of material – through-circulation. Another possible arrangement of flow geometry is cross-circulation when the air is passed over the open tray surface but it is not taken into account in this paper.

Though the entire case of woodchips drying seems very simple, the problem is the very existence of the suitable software. The packages that are now available have strongly limited capabilities. None of them is 3D simulation software. Hardly few deal with 2D geometries and only for a particular case. These are self-developed codes in some companies or institutions that need drying simulation software for their own unique-purpose use as for instance commercial DrySim [3]. Most of the other not numerous pieces of software are 1D or only heat and mass balance packages acting as a black box. To make things worse they require drying data as an input rather than an output of simulation. They are mostly designed as optimization tools. Some brief survey of the drying software is given below.

1.1 1D and balance software based on flow-charts

The capability of the commercial software of AspenTech corporation varies between particular versions. Overall commercial Apen Plus package is based on flow chart principles. The elements of the chart may be pumps, nozzles, fans, filters, separators, valves, etc. Almost everything that makes a scheme of chemical industrial installation. As such the software runs as an optimization tool for simulated schemes. The drying in version 7.3 is possible in indirect way by means of two blocks – stoichiometric reactor and flash separator [4]. The process of water evaporation from the solid is treated as pseudo-chemical reaction. The validity of output data is not assured. This is the user's task to input correct data and obtain the correct one. The usefulness of the package is restricted to the optimization of larger systems where the dryer block is one of elements.

Aspen Plus version 8.0 brings a drier block that can model 1D process [5]. This is a model of a continuous convective drier with counter or parallel flow of the wet feed and dry air. However, it still requires to input so many parameters than drying should be perceived as an input rather that an output of the simulation.

DryPack has been developed at Danish Technological Insitute in Aarhus. It consists of five separate modules. Two of them are interesting here: Batch Dryer Simulation Tool and Continuous Dryer Simulation Tool. Both tools are flow-chart based programs comprising elements of equipment that altogether make the dryer facility: pump, nozzles, ect [6] .

Simprosys [13] similarily as AspenPlus and DryPack is a flow-chart program. There are several widgets for the user to construct the drier scheme with the aid of a wide variety of supplementary devices: pumps, nozzles, fans, filters, separators, valves, heat exchangers, etc. As a flow chart program it is a tool for optimization of overall installation performance rather than 3D or 2D analysis of temperature, humidity, water content and other parameters field. Several process parameters should be put into the scheme from experimental data or other sources.

1.2 Expert systems

DrySel is a next piece of software of AspenTech. It is an expert tool supporting the user with selecting a dryer construction suitable to an assumed process.

1.3 2D simulation systems

DrySim is probably the only piece of drying software that deals more than one-dimensional simulation of drying. The package, like DrySpec 2, has been developed at NIZO (Netherlands) to simulate a spray dryer. But this package runs 2D simulation calculating the flow pattern, temperature, humidity and powder particles trajectory. The mathematical model comprises the Navier-Stokes equations with k-ε turbulence model [3].

1.4 Others systems

Process Manual is a web-based library of AspenTech too. It covers ten technical areas. One of them is a drying section divided on fourteen subchapters.

DrySpec2 is a program created at NIZO (Netherlands) as previously mentioned. The versatility is limited to particular setup, which is a two stage dryer of powder milk products. The first stage is a spray chamber whereas the other is a fluid bed dryer. Mass and thermal balances as well as psychrometric relations and sorption isotherms are included. However, according to their authors [3] the package acts partially as a 'black box'. The limited scope of the dryer construction and operation is a result of developing this package at NIZO for their own needs connected to food research.

DryPAK has been developed since 1990 at Łódź University of Technology by Z. Pakowski. At early versions communication was done through the text interface. The software is supposed to calculate heat and mass balance, drying kinetics and psychrometry.

No-name Excel-based tool [7]. a package contained in an Excel sheet focuses according to the authors on energy consumption optimization. Some calculations are performed with the aid of Visual Basic for applications (VBA) code.

The above review shows a severe shortage of 3D simulation tools for even such simple cases as batch convective dryers with nonagitating packed beds filled with pellet. Some of the aforementioned packages can not calculate drying output parameters. It is the user task to bring some valid drying data as the input data to the software. This is not only data for initial conditions but also characteristics of the process. So the usefulness is limited mostly to optimization aims. The problem of woodchips drying in a batch convective stationary fixed-bed dryer could be performed full way on neither of these packages. For more practical software the user should only put the initial data as a total mass of woodchips, their initial moisture content, X_1, inlet air temperature, humidity, φ, and mass velocity. As a result a 3D map of packed bed parameters should be obtained: moisture content X and temperature, T, of woodchips, respectively, and also other desire parameters. The existing software requires not only inlet parameters but also some internal process characteristics, for instance heat transfer coefficient, h, or drying constant, k, if the process is supposed to run according to the drying curve

$$\frac{dX}{dt} = -k(X - X_{eq}) \, , \tag{1}$$

where X_{eq} is the equilibrium moisture content, and t is the time. A reasonable approach to a 3D convective drying is to incorporate an existing computational fluid dynamics software. A very popular Ansys Fluent is an appreciated package for calculations of 3D flows both in external and internal aerodynamics. Fluent can be enriched to a certain degree with some libraries embedded in C dialect – user defined functions (UDF). So far there are three publications taking up the matter of incorporating the drying process into Ansys Fluent. These are a master thesis of Gullman [1], a neat work of Jung *et al.* [2] and two reports of Chourasia and Goswami [8, 9]. If it comes to both works of Chourasia and Goswami, they are not strictly connected to the drying process. Chourasia and Goswami calculate a state of quasi-equilibrium in a refrigerator chamber. The feed is a packed bed of potatoes that are brought into the equilibrium with cooling air and then kept at this state with regard to potatoes metabolic heat generation. The works of Gullman and Jung et al. refer strictly to drying issues. The former investigates a single tray of a chosen material, Jung *et al.* take a set of trays with silica gel. All four reports are reduced to 2D cases, though. Chourasia and Goswami, however, incorporates thorough-cirulation in their trays of potatoes bags. Since the thermal equilibrium assumption between phases was applied they used only one energy equation for the air flow and solid body – potatoes. This approach excludes the drying at the first period that is a nonequilibrium process.

Gullman and Jung *et al.* also take some extra simplifications (beside 2D flow). They investigate cross-flow over the surface of the dried material. So, the heat transfer coefficient at the interface of the material on the tray and the flow over it is a classic heat transfer coefficient. That is contrary to through-circulation where a volume heat transfer coefficient must be applied. The cross-flow simplification implies separate zone of flow and the solid body. That in turn makes handling the mesh in Fluent easier when nonequilibrium state between flow and the solid takes place. The most significant difference between the two approaches is that Gullman models his process by means of drying periods with constant temperature of the wet bulb at the first period, whereas Jung *et al.* run their process according to drying curve relation (1).

According to the author of this paper there have not been published so far any papers about incorporating 3D convective through-flow drying process of stationary fixed bed. Ansys Fluent seems a good piece of CFD software to incorporate drying model into it. The advantages are popularity among researchers, flexibility, versatility, possibility to link own UDF procedures to solver. The disadvantage are poor UDF documentation and poor documentation of handling some nonstandard mesh layouts.

2 Geometry and boundary conditions

A very simple geometry of the packed bed of woodchips and the flow duct is applied. The packed bed is not agitated. a strongly flattened cubic with dimensions 1.5 m×1.5 m×0.2 m with the last being the height, Fig. 1, is considered here. As it is shown the geometry is divided into three zones: the inlet, the drying zone and the outlet. The drying zone is 0.06 m high and 0.02 m offset from the velocity inlet surface. Some basic data is included in Tab. 1. The produced geometry reveals that through-circulation is considered here, i.e., the dried material is permeable and the air flows through the voids.

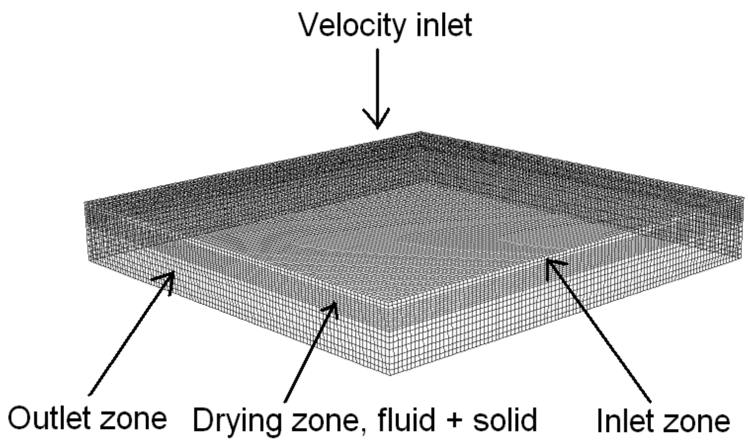

Figure 1: Geometry and the computational grid.

The mesh is uniform and the total number of cells amounts to 290 000. This number includes 100 000 cells in the drying zone. Taking into account that the geometry comprises not only the aerodynamic duct but also the solid body, the second solid mesh must be included. This is a so called double cell approach. The concept is developed according to the Ansys documentation mostly for heat exchangers. Since the packed bed is permeable two overlapping meshes should be incorporated in the drying zone: one for fluid body and one for solid body. The mesh for solid body has the same number of cells and the same layout as the mesh for fluid body so it is invisible in Fig. 1. Two separate meshes at the same location enable application of two energy equations for both bodies separately. Thus non-equilibrium simulation is possible with different temperature of flowing air and the dried feed. That takes place during the first period of drying when the temperature of dried material is constant – wet bulb temperature.

Table 1: Dimension of packed bed.

Full geometry dimension	Drying zone dimension	Drying zone volume	Drying zone lateral surface area
1.5 m× 1.5 m × 0.2 m	1.5 m × 1.5 m × 0.6 m	0.135 m^3	2.25 m^2

For simplicity it was assumed in theoretical model that the packed bed is filled with spheres as an equivalent of the complex in shape and shape-unique woodchip particle. For such a set of uniform in shape and diameter set it is easy to assess fundamental parameters of the packed bed like porosity, surface area, number of particles, etc. The porosity, ε, for a packed bed of equal diameter spheres depends only on the order packing arrangements as produced in Fig. 2. The first layout from the left side was chosen arbitrarily as well as the particle diameter. It is characterized by the largest porosity. The wood species is assumed to be a pine that affects only the conventional density. More detailed data of the premised characteristics of the woodchips feed is given in Tab. 2.

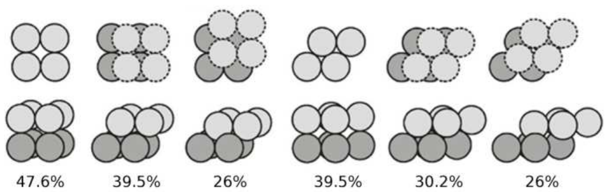

Figure 2: Ordered packing arrangement with porosity ε [10], with permission.

Table 2: Basic parameters of the woodchips packed bed.

ε	A	V	n	D_p	ρ_c
0.4764	21.21 m^2	0.0707 m^3	16875	20 nm	400 kg/m^3

As a convective drying is considered here, the drying medium is air that flows through the interface named velocity inlet in Fig. 1. Boundary conditions for the air velocity, temperature, humidity and packed bed moisture content are comprised in Tab. 3. One should note that velocity considered here is the superficial velocity. Initial moisture mass, m_w, is a secondary parameter calculated as a product of woodchips volume, conventional density and initial moisture content. The wood dry mass is found from definition of moisture content on the dry basis.

Table 3: Boundary conditions.

u	T_d	RH_1	X_1	X_2	m_d	m_w
1 m/s	60 °C	0%	0.42	0.2	28.27 kg	11.88 kg

3 Heat transfer and drying model

Heat transfer in packed beds is a complex problem still rather without a conclusive summary. The pellet in experiment or industrial processing is poured into a facility chamber whose bulk volume is known. The porosity can be estimated by means of robust mechanical methods. However, the total pellet surface area is not known. The same refers to the mean particle volume. Particularly the former is important in heat transfer calculations. Since the material is considered on a volume basis the heat transfer coefficient h that is usually expressed per square meter, m^2, in the drying technology is often volume based – m^3.

This work utilizes strictly determined layout of spheres so the total surface area is known and heat transfer coefficient on the surface basis is applied. A set of relations was proposed by Seader *et al.* [11] for a thin packed bed:

$$h = 0.151 \frac{G^{0.59}}{D_p^{0.41}} \left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right] , \ \mathrm{Re}_{D_p} > 350 \, ; [\mathrm{G}] = \left[\frac{\mathrm{kg}}{\mathrm{h\,m^2}}\right] , [D_p] = [\mathrm{m}] \ , \tag{2}$$

$$h = 0.214 \frac{G^{0.49}}{D_p^{0.51}} \left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right] , \ \mathrm{Re}_{D_p} > 350 \, ; [\mathrm{G}] = \left[\frac{\mathrm{kg}}{\mathrm{h\,m^2}}\right] , [D_p] = [\mathrm{m}] \ , \tag{3}$$

where D_p stands for particle diameter, G is mass flow rate in kg/(h m^2). Seader *et al.* gave a robust example of the drying estimation of a through-flow tray of 1.5 m^2 and cross-section a 5 cm high filled with cylindrical-shaped pieces of 6.35 mm diameter and 12.7 mm length. The ratio of the feed height to cross-section area equaled to 3.3 cm/m^2. The considered packed bed relative height does not excess it since the ratio amounts 2.67 cm/m^2. Seader *et al.* used their packed bed to estimate drying time during the first period between the initial and target moisture content on pure heat and mass balance.

The drying from humid air perception can be viewed as nearly adiabatic process of air humidification. From the point of view of the wet bulk the process can be described by means of drying curves which has an analytic form produced by formula (1) or the drying-rate curves. The latter is usually considered in a simplified way taking into account the first period of the constant-rate and only one second period of the falling-rate. The latter however, even if there are two distinct falling-rate periods is still considered as one period. Often as a linear decrease from X_c to X_{eq} for hygroscopic or capillary materials or to $X = 0$ for nonhygroscopic materials. Here only the constant-rate period is considered as an assumption since the woodchips particles are small and initial and final moisture contents are rather high. The drying rate is then the ratio of the transferred heat and the latent heat of water because of the equilibrium of heat and mass transfer:

$$R = \frac{h(T_d - T_w)}{\Delta H_w^{vap}} \left[\frac{\mathrm{kg}}{\mathrm{m^2s}}\right] , \tag{4}$$

$$R = \frac{h(T_d - T_w)A}{\Delta H_w^{vap}} \left[\frac{\mathrm{kg}}{\mathrm{s}}\right] . \tag{5}$$

The formula (4) of the relative drying-rate is useful if the total surface area of packed bed is known, but the absolute drying-rate (5) is more appropriate in application of water vapor source on a cell basis in Ansys Fluent.

An important feature of the first period is the constant temperature of the dried material. It is the wet bulb temperature. Its value is easily found in the Mollier humid air diagram at an intersection of the iso-enthalpy line, and the curve of saturation $RH = 100\%$. Analytical explicit finding of the wet bulb temperature T_w from an equation would be difficult as T_w in such equation is given in an implicit way. The advantage of the first period is the constant wet bulb temperature, that is invariable with the drying air temperature T_d. This enables high values of the air temperature without a risk of damaging the dried material.

4 Porous body

Since the dried material is represented in the physical model by spheres of the same diameter it is easy to determined fundamental characteristics impacting the flow pattern. The general equation for pressure drop in porous medium is given by

$$\nabla p = -\frac{\mu}{\alpha}\mathbf{u} - \sum_{j=1}^{3} \mathrm{C}_{2ij}\left(\frac{1}{2}\rho u_j|\mathbf{u}|\right), \tag{6}$$

where C_{2ij} stands for a matrice of inertial resistance factor, α – for permeability, μ – dynamic viscosity, and $\mathbf{u}$ is the velocity vector. The right hand side of Eq. (6) is substituted into the momentum equation as a source term. For the one-dimensional homogenous packed bed of spheres the Ergun equation enables to identify the aforementioned coefficients.

$$\alpha = \frac{D_p^2}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2}, \tag{7}$$

$$C_2 = \frac{3.5}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3}. \tag{8}$$

For the diameter D_p and porosity ε given in Tab. 2 the values of α and C_2 are presented in Tab. 4. They are input parameters in Cell Zone Conditions for the drying zone shown in Fig. 1.

5 Governing equations

In this study liquid water does not exist in the computational domain. Water is transfered in the drying zone (Fig. 1) of the domain in vapor state

Table 4: Evaluated values of resistance coefficients.

a	C_2
950857 1/m^2	847 1/m

as a source term in the continuity equation. Therefore there was no need to apply multiphase model and the equations are applied for the single phase, therefore they can be written as

$$\frac{\partial(\varepsilon\rho)}{\partial t} = \nabla\cdot(\varepsilon\rho\mathbf{u}) = S_m\,, \tag{9}$$

$$\frac{\partial(\varepsilon\rho)\mathbf{u}}{\partial t}+\nabla\cdot(\varepsilon\rho\mathbf{u}\mathbf{u}) = -\varepsilon\nabla p+\nabla\cdot(\varepsilon\boldsymbol{\tau})+\varepsilon\mathbf{B}_f-\left(\frac{\varepsilon^2\mu}{\alpha}\mathbf{u}+\frac{\varepsilon^2 C_2}{2}\rho|\mathbf{u}|\mathbf{u}\right), \tag{10}$$

$$\frac{\partial}{\partial t}(\varepsilon\rho E)+\nabla\cdot\Big(\mathbf{u}(\rho E+p)\Big) = \nabla\cdot\Big(\varepsilon k\nabla T+(\bar{\boldsymbol{\tau}}\cdot\mathbf{u})\Big)+h_{fs}A_{fs}(T_s-T)\,, \tag{11}$$

$$\frac{\partial}{\partial t}\Big((1-\varepsilon)\rho_S E_S\Big) = \nabla\cdot\Big((1-\varepsilon)k_S\nabla T_s\Big)+h_{fs}A_{fs}(T-T_S) \tag{12}$$

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\mathbf{u}Y_i) = -\nabla\cdot\mathbf{J}_i+S_i\,. \tag{13}$$

The term $\boldsymbol{\tau}$ stands for the stress tensor, $\mathbf{u}$ – air velocity vector E – total fluid energy, E_s – solid medium energy, h_{fs} – heat transfer coefficient [W/m^{2}K], A_{fs} – interfacial area density, $\mathbf{B}_f$ – volume forces, $\mathbf{J}_i$ – diffusion flux of species i due to gradients and temperature. The product of h_{fs} and A_{fs} is the consequence of volume based heat transfer in Ansys Fluent in double cell approach. A_{fs} must take a value corresponding to the woodchips total surface area. That is the user's task to calculate it and set into Fluent. The Eqs. (9)–(11) form the standard set of equations of flow with the heat exchange. The second energy equation (12) for solid medium is required due to nonequilibrium between it and the fluid. Since the existence of vapor species in the flow, species transport equation is added to the set (13) i in the last equation stands for species number, however, there are only two species in this modeling: air and water vapor. The source term of the species mass source of the vapor in Eq. (13) closely refers to mass source S_m in the continuity Eq. (9). Y_i is species mass fraction, simply moisture content in air. The other expression on the right hand side of the species transport equation stands for diffusion flux. Both energy equations contain a source term of the fluid-solid heat exchange due to non-equilibrium, which are $h_{fs}A_{fs}(T - T_s)$ for the fluid and $h_{fs}A_{fs}(T_s - T)$ for the solid.

6 Numerical method

In this study modeling and simulation of the three-dimensional convective, through-flow, nonagitating, packed bed drying was performed with a commercially available CDF code Ansys Fluent. The species model and the energy model were utilized for the purpose of the calculation of the psychrometry and the heat transfer. Due to that and because no water was stored in a liquid state in the computational domain (drying zone in Fig. 1) there was no need to apply the multiphase model. All water in vapor form was delivered to the air flow as a source term in Eq. (9). In Ansys Fluent environment it was done by UDF macro DEFINE_SOURCE into which Eq. (5) was incorporated. Since the macro is run on cell basis the overall pellet surface a must be divided by the number of cells in the drying zone.

The wet bulb temperature, T_w, of the mesh referring to the solid medium was set in the DEFINE_PROFILE macro. The liquid water, though absent in Fluent, is incorporated in each cell as something like 'virtual water' in the drying zone as a cell variable – a C_UDMI() macro. Thus it is possible to track the water that has evaporated and the remaining part. To set the water quantity at the beginning of the simulation as a boundary condition a DEFINE_INIT() macro is applied. When the simulation is run the macros of the iteration loop are used to calculate the remaining water at each step: DEFINE_SOURCE andDEFINE_EXECUTE_AT_END. If a first cell in the drying zone reaches the assumed X_2 moisture content the simulation is stopped by means of a suitable command in the latter. Some Fluent accessible parameters like interfacial area density, heat transfer coefficient ect. are incorporated via DEFINE_PROFILE macros, since they must be accessible as variables in the described UDF.

A set of circumstances led to neglect turbulence modeling. The heat exchange coefficient given by formulae (2), (3), that is the main factor affecting vapor rate into the flow is independent of turbulence. Secondly, the velocity at the inlet is uniform and remains such at the outlet. Due to these constraints the vapor flux rate distribution should be one-dimensional with respect to the flow direction.

As the water content changes with elapsed time transient calculation was performed. The standard SIMPLE algorithm was used for pressure-velocity coupling method. The second order upwind discretization scheme was chosen for momentum, energy and vapor transport equation. Twenty iterations were performed at each time-step. The velocity in the drying zone was set to physical velocity.

7 Results

Due to the aforementioned simplifying constraints – uniform inlet velocity, homogeneous porous body drying zone and heat transfer coefficient irrelative to turbulence intensity the results are one dimensional with respect to the longitudinal axis. Hence only the air temperature distribution from the outlet view is produced here, Fig. 3. As one can see the air temperature at the outlet is uniform and the only variation takes place along the flow axis z. Due to the lateral homogeneity the other charts are shown along flow axis only.

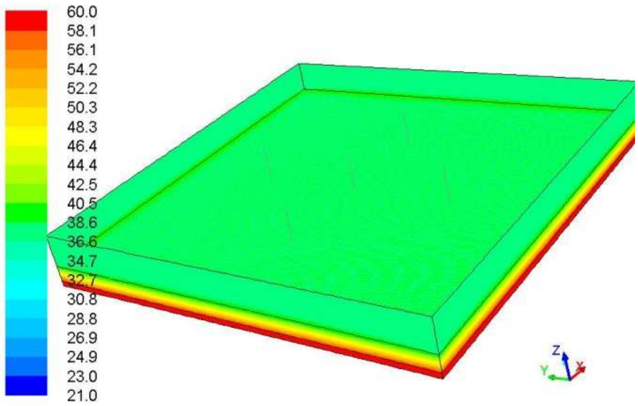

Figure 3: Air temperature distribution.

The drying air temperature as well as the wet bulb temperature are produced in Fig. 4. The air temperature is marked with black squares. The initial value diminishes from 60 °C to 37.7 °C and the decrease is exponential as this is an equivalent situation to the heat exchanger with one side isothermal. The solid medium temperature is constant at the wet bulb temperature 21 °C marked with a bold line. Both temperature distributions are valid as long as first parts of the packed bed reach the final moisture content $X_2 = 0.2$ which was set as a premise as the critical moisture content, X_c. Hence the curves remains fixed till the calculation stop.

The result of continuous one-dimensional calculation may be easily compared to robust balance estimation on the 'black box' basis. If one took into consideration only the hot air input and output there would be no distributions of parameters but only discreet drop of air parameters between inlet and outlet. The drying rate would be uniform in the entire volume of the 'black box', hence one should expected higher drying rate and heat exchange in such circumstances. Thus a simple use of formulae (2)–(5) and a formula for heat capacity yield the much lower air outlet temperature 26.2 °C. The latter is produced in Fig. 4 with a solid line.

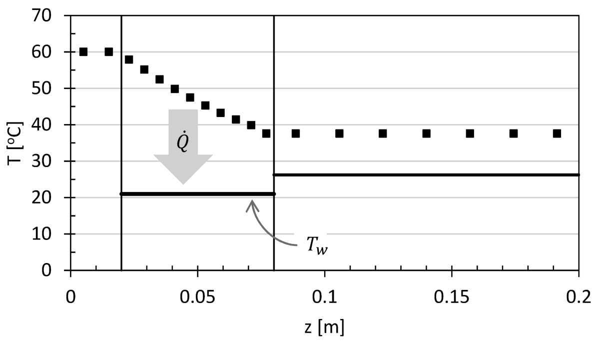

Figure 4: Air temperature distribution with drying zone position between the vertical lines.

The relative humidity of air is shown in Fig. 5. It increases from its initial value $RH = 0\%$ at the inlet of the drying zone ($z = 0.02$ m) to $RH = 22.2\%$ at $z = 0.08$ m. The balance calculation ('black box') yields much higher outlet value of $RH = 63\%$.

Figure 6 shows moisture content in solid medium at the beginning of the process $X_1 = 0.42$ and at the end of the process with $X_2 = 0.2$ at the air inlet and $X_2 = 0.32$ at the outlet. The result is obtained after $t = 205$ s of drying. So, the moisture content between the inlet and the outlet is strongly varied ($\frac{0.1}{0.22} = 0.45$) even for such a thin drying zone – 6 cm of thickness, 2.25 m^2 of cross-section. Balance calculations give a uniform level of $X_2 = 0.2$ and slightly earlier at $t = 195$ s.

The drying rate on the volume basis [kg/m^{3}s] is produced in Fig. 7. At the inlet to the drying zone $R = 0.22$ kg/m^{3}s and decreases to $R = 0.1$ kg m^3/s at outlet. Balance calculations yield the value, of $R = 0.237$ kg/m^{3}s (4) for the entire drying zone.

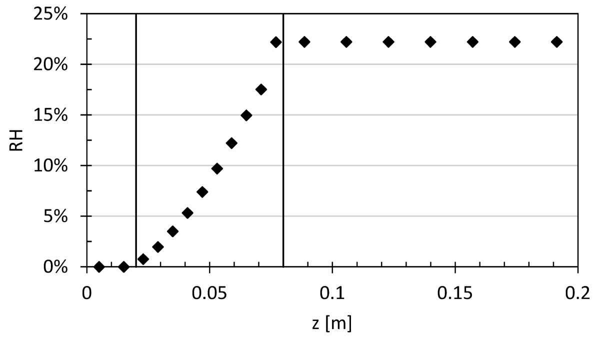

Figure 5: Relative humidity distribution.

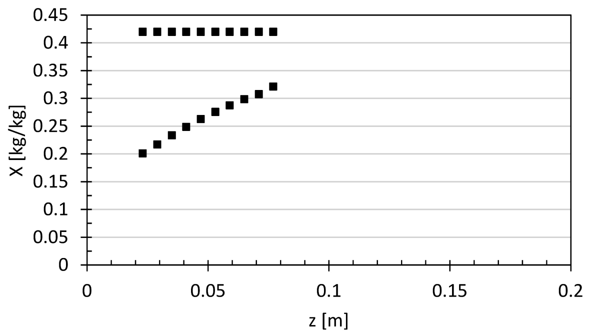

Figure 6: Initial and final moisture content in the drying zone.

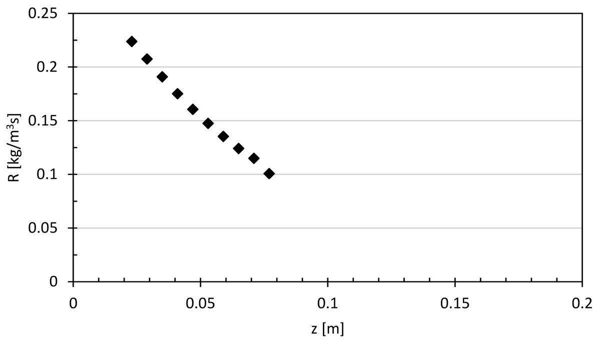

Figure 7: Drying rate.

8 Conclusions

Three-dimensional convective drying with through-flow layout was successfully implemented into Ansys Fluent by means of linking UDF procedures. The feed of wet woodchips was modeled as a packed bed spheres of the same diameter and then its parameters were introduced into porous model of Fluent. The aim of the procedure was to avoid arduous creating of computational mesh containing large amounts of spheres. The first period of drying characteristics were incorporated. However, not only vapor flux into the flow was incorporated, that is equivalent to drying of solid medium, but also the water storage. The latter was performed by means of memory variables.

Though the packed bed is relatively thin with its thickness amounting to 6 cm and the cross-section 2.25 m^2, the results of simulation differ substantially from plain balance calculations in its quantitative aspect. It seems that balance calculations essentially overestimate drying efficiency. The presented results are one-dimensional but it is not due to the imposed simplifications upon the tested drying model but due to the most simple geometry. A slightly enhanced geometrical model equipped with an air duct – pipe, pipe bends and diffuse certainly would give a three-dimensional field. Hence, even at the current stage of development the described model is already useful.

Some improvements of UDF library should be incorporated like the wet bulb temperature that is now input as parameter but should be calculated from initial air parameters in isentropic process of air moisturizing. The main impact of the further development, though, should focus on reliable simulations of much thicker packed beds – about 0.5 m thickness and the same cross-section as in the present paper. Hence the second period of drying should be incorporated. That implies implementing a reliable method for deriving a value of critical moisture content X_c. a detailed study should be put on the heat exchange coefficient, validity of available formulae and extent of their application since it is the crucial factor in the first period of drying.

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