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Biomass drying: Experimental and numerical investigations

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Abstract Results of experimental and numerical investigations of wood chips drying are described in the paper. Experiments are carried out on two test facilities: a small laboratory rig and a larger pre-prototype dryer. Both facilities are thorough-circulation convective air dryers. The first one is a batch dryer, whereas the second one is a continuous dryer with wood chips flowing down by gravity from a charging hopper to a gutter with the aid of screw-conveyor. The latter is considered a half scale model (pre-prototype) for professional drying installations. A low feeding rate of wood chips into the pre-prototype dryer makes the process quasi-stationary and the difference between it and a batch drying is negligible. So, most experiments at this facility were carried out as batch dryers with non-agitated packed beds. The investigations exhibit the same linear correlation between the mass of evaporated water from the packed bed and the drying air velocity for both facilities. Numerical analysis of the drying process is conducted using the Ansys Fluent software enriched in drying capabilities by means of self-written procedures – user defined functions. Simulations confirmed a phenomenon of a drying front observed in the small laboratory rig. A thin layer of wood chips comprises the whole heat exchange and moisture evaporation phenomenon. The drying front travels downstream in the course of the process separating the already dried layer and still wet layer.

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Nomenclature

A	–	surface area of the porous packed bed, m^2
A_p	–	mean woodchips particle surface area, m^2
A_{fs}	–	interfacial area density (ratio of the area of the fluid-solid interface and the volume of the porous zone), 1/m
C_2	–	inertial loss coefficient, m^{-1}
c_p	–	wood specific heat, kJ/kgK
d_p	–	mean particle diameter, m
h	–	convection heat transfer coefficient, W/m^2K
l	–	length, m
m_d	–	mass of dry wood chips, kg
m_p	–	vapor mass, kg
m_s	–	bone-dry wood chips mass, kg
m_w	–	water mass, kg
p_s	–	saturation pressure, kPa
p_{dyn}	–	dynamic pressure, Pa
R	–	drying rate, kg/m^2s
r_w	–	evaporation heat, kJ/kg
t	–	time, min.
T	–	temperature, °C
T_1	–	temperature at the inlet to the packed bed, °C
T_s	–	air saturation temperature, °C
T_w	–	wet bulb temperature, °C
u	–	air velocity in the feeding duct, m/s
U_1, u_1	–	air inflow velocity, air superficial velocity in the packed bed, m/s
V_p	–	mean particle volume (woodchips), m^3
W	–	wood moisture content on a wet-solid basis, $W = 100X/(100 + X)$, %
X	–	wood moisture content on a dry-solid basis, kg/kg, %
X_c	–	critical moisture content, kg/kg, %
X^*	–	wood equilibrium moisture content (dry-solid basis), kg/kg, %
Y	–	mass humidity (air), kg/kg
z	–	length along z axis, m

Greek symbols

α	–	permeability of the packed bed, m^2
ϵ	–	porosity, %
φ	–	relative humidity (air), %
μ	–	dynamic viscosity, kg/m s
λ_p	–	wood thermal conductivity, W/mK
ρ_u	–	wood conventional density, kg/m^3
ρ	–	woodchips bulk density, kg/m^3

Subscripts

1 – initial
2 – final

1 Introduction

Material drying is a common engineering process associated with removal of moisture. Dzurenda and Banski [1,2] point out that a relative wood moisture content increase form $W = 10\%$ to $W = 60\%$ (percent points) decreases thermal efficiency of a wood fed boiler form $\eta = 91.15\%$ to $\eta = 86.97\%$ at the flue gas temperature $T = 120\,^{\circ}\mathrm{C}$. It seems only $\Delta\eta = 4.18\%$ of percent points, but in a long term economics it may be important.

Because of diversity of dried materials and physical state of wet matter (liquid, solid) and moisture medium, the drying conditions may be significantly different. The difference causes also the fact whether the dried material is in a stationary layer or a dried layer is agitated. Most of the literature relates to the drying of solid materials, and these may have a different form, e.g. granule, powder, briquettes, etc. The most common installations are those where convection drying with hot air or a mixture of air and exhaust gases as a drying medium takes place. Less popular are solutions where material is heated directly, e.g., based on induction or electromagnetic radiation.

In a typical plant were pellets are produced, the technological chain includes processes of drying sawdust from which pellets are produced and drying wood chips which are gasified for heat. Wood chips are treated as fuel for further gasification [3,4]. The obtained syngas is then burnt and used for drying sawdust. But also wood chips are required to be dried before entering gasifier. Drying of the wood chips prior to supplying to a gas-generator makes it possible to produce more syngas. Greater amounts of produced syngas may be delivered not only to the process of sawdust drying, but can also be fed to an engine which runs a generator producing electric energy. In such way the co-generation circuit, where pellets and electric energy are produced, is created. The commercial appeal of the drying process of wood chips can be enhanced as waste heat form the co-generation engine that can be again used for wood chips drying.

In order to increase the calorific value of syngas, wood chips should be dried to decrease moisture content down to $W = 20\%$. A gas generator with power output of 4 MW [3] requires chips at a rate of 1000 kg/h with the aforementioned moisture content. If the dryer was fed with wood chips with the moisture content of $W = 43\%$, the stream of chips should be depleted of 400 kg of water per hour. In case of wood chips with moisture content of $W = 47\%$, the amount of evaporated water should be 500 kg per hour, respectively.

The paper presents results of experimental investigation of wood chips drying and numerical studies of the process. A comparison of the obtained experimental and numerical results is also presented. Experiments are carried out on two test two test facilities: a small laboratory rig and a larger pre-prototype dryer.

The number of computer programs to simulate the drying process is relatively small. They are mostly created in academic centers and institutes and are usually dedicated to strictly defined applications.

In some cases attempts are made to build drying software on the simplest information technology tools such as Ms Excel – see Kudra *et al.* [5], whereas at the opposite side are relatively complex software packages like Simprosys [6,7] or DrySPEC2 [8,9]. In this paper numerical investigation of the drying process is carried out using the Ansys Fluent program, primarily designed for fluid mechanics. Self-written procedures in *C* language are accordingly supplied to extend Fluent capabilities to modeling the drying processes.

2 Laboratory test rig

2.1 Methods of investigations

A laboratory test rig shown in Figs. 1 and 2 has been designed and built at the Institute of Fluid-Flow Machinery in Gdansk for studying drying processes. The main elements of the rig are: measurement column made of organic glass in which the drying process has been accomplished, a mesh grate on which the wood chips were settled, an electric air heater, a fan forcing air through the packed bed and on the top of facility a measure tube in which air velocity was measured with a Prandtl tube. The column was made of organic glass to enable visual observations of phenomena occurring inside it. Heated air was used as a drying agent.

Thirty series of measurements were carried out on the laboratory rig shown in Fig. 1 and photographed in Fig. 2. Experiments were conducted for the following set of parameters: the velocity of air flowing into the packed bed that was set every time in the range 0.65–1.4 m/s, the initial moisture contents of wood chips that was held at $W = 50$–55%, the initial mass of wet wood chips usually amounted to 9–10 kg, the temperature of the drying air was equal in most cases to 60 °C and finally the drying time was usually about one hour. Moisture content of wood chips was defined by means of a classic formula [10]:

$$W = \frac{m_w}{m_w + m_d} \times 100\% \,, \tag{1}$$

where: W – humidity of wood chips, m_w – mass of water in wood chips, m_d – mass of dry wood chips.

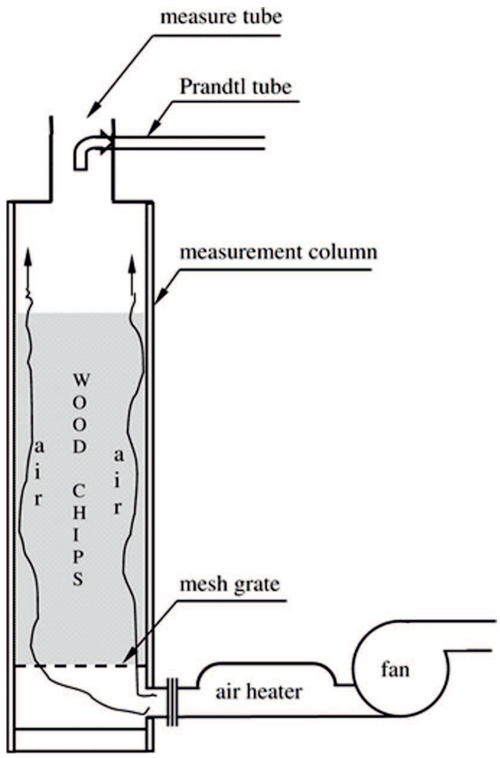

Figure 1: Scheme of the laboratory rig for biomass drying investigations.

A batch of wood chips intended for investigation was scrupulously mixed before every measurement and stored a few days in plastic bags. This way of preparation of wood chips made it possible to obtain uniform moisture content all over the batch. Several control measurements confirmed the same moisture content within the whole batch. Chips prepared in that

Figure 2: Photo of the laboratory facility.

way were then strewn into the measurement column whose net weight was 9.3 kg. The mass of the column filled with wood chips up to the height of 0.4–0.7 m equaled 15–22 kg in several measurements. The so prepared column of wood chips was then connected to a system of air supplying – a blower and a heater. The system was equipped for measuring temperature, air flow rate and pressure drop of air in the layer of wood chips in the column. The desired temperature of air flowing out from the heater was set by a controller. In most investigations the temperature of air at the exit from the heater was 65 °C and temperature of flow through the packed bed was 60 °C. The duration of a single drying process varied from 40 to 80 min depending on the moisture content of wood chips. The process was stopped at the moment when the assessed mass of evaporated water was at least one kg. After the end of the drying process the column was disconnected and weighed together with its content. The difference between the weight of the column before drying and after it meant the loss of moisture in the packed bed of the dried wood chips. Knowing the weight of dried wood chips and their initial moisture content and further knowing the weight of the dried wood chips, one could easily calculate the moisture content of wood at the end of the drying process.

2.2 Detailed results of laboratory investigations

Investigation results are shown in Tabs. 1–4 and in Fig. 3. Descriptions of most fields in Tabs. 1–4 seem obvious, however, some explanations will be put here. Moisture contents of wood chips before and after the drying

Table 1: Measured and calculated quantities (part I).

Parameter	Symbol	Unit	Number of measurements						
			1	2	3	4	5	6	7
Weight of column with wood chips before drying		kg	19.75	17.7	17.25	17.24	18.5	17.26	18.9
Weight of column with wood chips after drying		kg	16.5	15.6	14.9	14.75	16.1	14.74	16.75
Amount of evaporated water	m_w	kg	3.25	2.1	2.35	2.49	2.4	2.52	2.15
Time of drying	t	min.	62	45	74	60	48	62	44
Moisture content of wood chips before drying process	W	%	42.5	30.8	32.5	42.5	40	40	43
Moisture content of wood chips after drying process	W	%	16.7	7.6	4	16.3	18.8	12.2	27.7
Thickness of the packed bed in the column		m	0.58	0.6	0.45	0.41	0.58	0.45	0.6
Pressure drop in the packed bed		H_2O	65	57	90	83.7	65	80.6	60.7
Dynamic pressure in the measurement tube	p_{dyn}	Pa	86	91	46	56	80	51	85
Air velocity in the measurement tube	u	m/s	12.2	12.3	8.3	9.8	11.7	9.4	12.06
Superficial velocity of the packed bed	u_1	m/s	1.28	1.3	0.87	1.03	1.23	0.99	1.27
Temperature of the column wall		°C	44	42	43	45	45	45	
Ambient temperature		^{o}C	24	27	28	24	26	24	27
Bulk density of wet wood chips	ρ	kg/m^3	273	213	267	293	240	260	242
Amount of water evaporated per minute		kg/min	0.052	0.047	0.032	0.0415	0.05	0.0406	0.049
Amount of water evaporated per square meter per hour		kg/h/m^2	47.3	42.7	29	37.8	45.45	36.9	44.5

process were measured on randomly chosen samples and then averaged. Further these values were assumed constant for the entire volume of the drying. The term *thickness of the packed bed in the column* should be understood as the height of column above the grate covered by chips, as depicted in Fig. 1. *Dynamic pressure in the measure tube* refers to the dynamic pressure of the air flow measured with the Prandtl tube placed in the

Table 2: Measured and calculated quantities (part II).

Parameter	Symbol	Unit	Number of measurements						
			8	9	10	11	12	13	14
Weight of column with wood chips before drying		kg	19.6	16.9	17.25	16.9	17.5	17.5	18.25
Weight of column with wood chips after drying		kg	16.9	14.65	15.05	14.5	14.6	15.05	16.05
Amount of evaporated water	m_w	kg	2.7	2.25	2.2	2.4	2.9	2.45	2.2
Time of drying	t	min.	51	61	60	70	83	61	69
Moisture content of wood chips before drying process	W	%	42	49.25	42.5	44.9	46.14	48.2	52
Moisture content of wood chips after drying process	W	%	21	26.5	20.52	19.4	16.6	26.1	36.7
Thickness of the packed bed in the column		m	0.6	0.4	0.45	0.4	0.405	0.41	0.4
Pressure drop in the packed bed		H_2O	65.7	69.4	69.4	65	66	65	86.8
Dynamic pressure in the measurement tube	p_{dyn}	Pa	83	46	50	49	40	50	35.7
Air velocity in the measurement tube	u	m/s	12	8.9	8.5	9.1	8.23	9.3	7.8
Superficial velocity of the packed bed	u_1	m/s	1.26	0.94	0.98	0.96	0.87	0.98	0.82
Temperature of the column wall		°C	45	45	45	41	43	42	43
Ambient temperature		°C	28	26	26	27	26	26	27
Bulk density of wet wood chips	ρ	kg/m^3	260	288	267	288	307	310	339
Amount of water evaporated per minute		kg/min	0.053	0.037	0.037	0.034	0.035	0.04	0.032
Amount of water evaporated per square meter per hour		kg/h/m^2	48.2	36.6	36.6	30.9	31.8	36.4	29

measure tube, located at the top of the facility. This pressure was further recalculated into the air velocity and then into the superficial velocity at the cross section of the drying section of the column. *Bulk density of wet wood chips* should be understood as a ratio of the total weight of wood chips particles to the occupied volume of the column.

Table 3: Measured and calculated quantities (part III).

Parameter	Symbol	Unit	Number of measurements						
			15	16	17	18	19	20	21
Weight of column with wood chips before drying		kg	17.6	19.1	20.75	18.2	16.65	20	19.2
Weight of column with wood chips after drying		kg	15	16.7	17.5	16.35	14.75	17.35	16.65
Amount of evaporated water	m_w	kg	2.6	2.4	3.25	1.85	1.9	2.65	2.55
Time of drying	t	min	90	50	60	45	37	50	46
Moisture content of wood chips before drying process	W	%	48	47	48	42	40	40.5	43.5
Moisture content of wood chips after drying process	W	%	24.2	29.5	27.3	26	20	21	23.8
Thickness of the packed bed in the column		m	0.4	0.59	0.6	0.5	0.4	0.6	0.5
Pressure drop in the packed bed		H_2O	88	65	66.3	59.5	69.4	80.6	72
Dynamic pressure in the measurement tube	p_{dyn}	Pa	35	79.3	79	90	94	80	90
Air velocity in the measurement tube	u	m/s	7.8	11.8	11.8	12.4	12.5	11.8	12.4
Superficial velocity of the packed bed	u_1	m/s	0.82	1.24	1.24	1.31	1.32	1.24	1.31
Temperature of the column wall		°C	40	43	46	45	47	46	45
Ambient temperature		°C	23	26	27	29	29	30	29
Bulk density of wet wood chips	ρ	kg/m^3	314	251	289	269	278	270	300
Amount of water evaporated per minute		kg/min	0.029	0.048	0.054	0.041	0.051	0.053	0.055
Amount of water evaporated per square meter per hour		kg/h/m^2	26.4	43.6	49.1	37.3	46.3	48.2	50

During the drying process in the laboratory rig the moisture content of wood chips W dropped from 30–53% to 20–29%. The summary of this data is the drying effectiveness shown in Fig. 3. The abscissa marks the superficial velocity of the packed bed and the ordinate marks the relative mass of evaporated water. The latter is normalized with the column cross-section and the drying time. The temperature of the heated air is considered

Table 4: Measured and calculated quantities (part IV).

Parameter	Symbol	Unit	Number of measurements							
			22	23	24	25	26	27	28	29
Weight of column with wood chips before drying		kg	18.55	19	18.75	19.85	17.75	19.9	18.55	18.3
Weight of column with wood chips after drying		kg	15.3	15.25	17.15	18.2	16	17.55	17.45	16.6
Amount of evaporated water	m_w	kg	3.25	3.75	1.6	1.65	1.75	2.35	1.1	1.7
Time of drying	t	min	60	80	57	57	58	78	45	60
Moisture content of wood chips before drying process	W	%	47.5	48.5	45.7	52.3	39	56	45.7	45
Moisture content of wood chips after drying process	W	%	18	16	21.1	43.5	23	43.4	38.4	34.6
Thickness of the packed bed in the column		m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pressure drop in the packed bed		H_2O	69.4	75	22	27.3	24	22	19	23.5
Dynamic pressure in the measurement tube	p_{dyn}	Pa	93	95	30	29	29	25	27	26
Air velocity in the measurement tube	u	m/s	12.6	12.8	7.2	7	7	6.5	6.8	6.6
Superficial velocity of the packed bed	u_1	m/s	1.33	1.35	0.76	0.74	0.74	0.69	0.72	0.7
Temperature of the column wall		°C	46	47	46	45	45	45	45	45
Ambient temperature		°C	29	29	29	31	31	30	30	29
Bulk density of wet wood chips	ρ	kg/m^3	280	294	285	318	256			
Amount of water evaporated per minute		kg/min	0.054	0.047	0.028	0.029	0.03	0.03	0.024	0.028
Amount of water evaporated per square meter per hour		kg/h/m^2	49.1	42.7	25.5	26.4	27.3	27.3	21.8	25.4

constant, though some slight variability affected measurements. The main characteristic of the process is a linear dependence of the relative drying rate on the air velocity. It should be pointed out that several other factors which were not recorded nor considered and variables here might have an impact on the drying process and some data scatter.

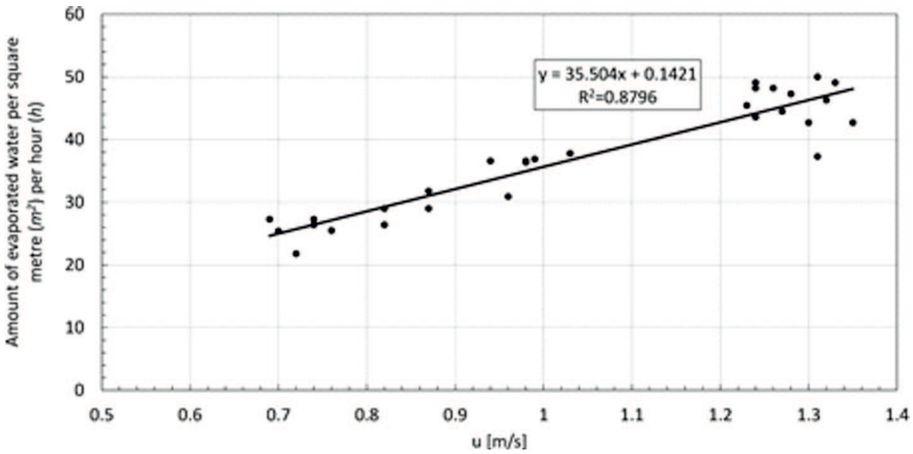

Figure 3: The amount of water evaporated per square meter of the small laboratory rig per one hour versus inlet air velocity.

Figure 4: Dew point occurence in the packed bed.

Appearance of a dew was easily observed. It manifested itself by appearance of water layer at the inner surface of the tube, Fig. 4. This is an effect of vapor condensation on the wall of the drying column. Since the air exiting the zone of dried wood chips is saturated, even a small heat transfer through the wall and the subsequent wall temperature decrease starts condensation on it. Inside the tube a thin layer separating dried and still undried zones of wood chips can be found. It is splayed across the packed bed and is visible where it touches the tube wall. This layer acts as a drying front. As it travels downstream (upwards with respect to the rig layout) the dried mass of wood chips is left behind and still non-dried remains ahead. The phenomenon of the traveling drying front is much better visible on a packed bed of smaller particles – sawdust, Fig. 5.

Figure 5: Drying interface in the small laboratory rig.

Results of the drying process of wood chips seem to confirm the possibility of drying of wood chips in a quasi-stationary layer. It is purposeful to develop a theoretical model of the drying process, which will enable us to identify physical properties and other parameters of experiments, determine drying procedure and the drying rate.

Besides drying the wood chips, in the same laboratory rig, a series of drying sawdust in a similar manner were carried out. This series also seems to confirm the possibility of drying sawdust in a quasi-stationary packed bed. In this case the parameters of the drying agent and sawdust geometry of the dryer should be different from that proposed for the drying of wood chips. This is due to the fact that air flow was so fast, that it raised a layer of the dried sawdust, what is shown in Fig. 6. Even a small increase of air velocity, was lifting up the layer of sawdust higher and higher, until a sudden ejection through the measure tube.

Figure 6: View of the sawdust layer lifted above the grate.

3 A pre-prototype dryer

3.1 Dryer construction and methods of investigation

The dryer used in these experiments is a prototype whose layout closely resembled a target unit dedicated for the pellet plant. Also, parameters of the prototype dryer are similar to those that are expected in the real cogeneration system. It is considered that the dryer unit might serve not only for wood chips drying but also for drying other biomass types. The picture of the dryer is shown in Fig. 7.

The main elements the prototype dryer shown in Fig. 7 are: drying chamber, air heater, fan, charging hopper, screw conveyor, the system controlling the screw conveyor, diffuser, confusor, air ducts, filter bag. The air circuit was an open loop and movement of air was forced by the fan. Air was heated by an electric heater. Mass flow rate of air was calculated on the basis of flow velocity. The latter was measured as a difference of dynamic – static pressure using a Prandtl tube that was mounted at the center axis of a feeding tube of diameter 0.25 m. It was considered reasonable to make an assumption that the velocity in the pre-prototype dryer may be different that the one in the laboratory rig. Holding equal velocities for both facilities would be difficult due to power demand for the air heating and limited compression ratio for the pre-prototype dryer.

In the first stage of investigations, tests were conducted while drying wood chips, being a raw material for the production of syngas. Wood chips were supplied to the charging hopper at the top of the dryer and at the time

Figure 7: Prototype dryer.

of measurement the whole volume of the dryer was filled with them. The wood chips path from the inlet to the outlet followed the pattern: charging hopper, drying chamber and the gutter at the bottom. Two of the opposed walls of the drying chamber were made of perforated metal plates in order to prevent chips spilling through the air inlet or outlet. The diameter of perforations was 0.0015 m. Air flowed into the drying chamber and out of it through these perforations. The plate through which air flowed out was adjustable in order to enable changing the thickness of the packed bed. Inside the gutter a screw conveyor was mounted for removing dried material. Interestingly, observations seem to indicate that the outflow of the packed bed does not carry away tiny wood particles. The scrutiny of air ducts and the bug filter reveals a slight amount of deposit. A special attention was paid to:

- moisture content uniformity of wood chips samples subject to drying,
- reliability of woodchips samples taken for moisture content measurements,
- drying time in order to make it close to the professional dryer that should work in the actual plant.

After the homogenization, the specific gravity of the selected batch of chips was known, by weighing a known volume of chips. The procedure of chips conditioning was performed once before a series of drying experiments. Obviously, granulation distribution of chips and their moisture content were further homogenized on their way through the charging hopper, drying chamber and the gutter. Four samples of chips from the prepared batch were collected and moisture content of each was measured.

The experiments were conducted for the initial chips moisture content W between 22% and 50%. This range was chosen since industrial dryers of wood chips are fed with raw material of this range of wetness. The drying process with a low feeding rate of wood chips differs only slightly from the stationary drying process. That enabled immersing chips samples into the stationary packed bed and their withdrawal for further proceeding after the particular drying process had been completed. The volume of the drying chamber, mass flow and temperature of air were matched so that the packed bed should be dried by one hour.

During investigations of wood chips drying process at the mid-height of drying chamber, along the flow path of the passing air three mesh bags of the same volume and shape were placed one after another, which is shown in Fig. 8 and also schematically in Fig. 9. Symbols P_1, P_2, P_3 denotes bags witch chip samples. Their ordinal numbers are consistent with the distance from the air inlet. In subsequent figures and tables they are equivalent to zones A, B, C of the drying chamber, respectively. The bags were made of mesh, which did not caused pressure drop of air through-flow. Before filling the bags, wood chips were homogenized by manual mixing and then a small amount of so prepared chips was taken to measure their moisture content.

Before placing bags filled with chips in the drying chamber they were weighed. The weight was determined to the nearest tenth of gram. The wetness of sample bags was the same as the wetness of the surrounding packed bed. The whole facility was filled with chips – from the gutter at the bottom up to the inlet of the charging hopper. Then, the hopper was covered with a plate so as to limit the leakage of air. After such preparations, airflow was turned on and drying process of wood chips started. Only little air outflowed through the hopper inlet and gutter outlet. This quantity was estimated to be about 10% of the total flow and caused a small error in the evaluation of the amount of air flowing through the bags.

The drying process usually took about 60 to 90 min and was dependent mostly on the moisture content of wood. After completion of the drying process the bags with wood chips were taken out and weighed. Knowledge of the weight and moisture content of the samples before and after drying made it possible to calculate the moisture content of the packed bed after drying and the mass of evaporated water.

Figure 8: Sample bags in the dryer hopper.

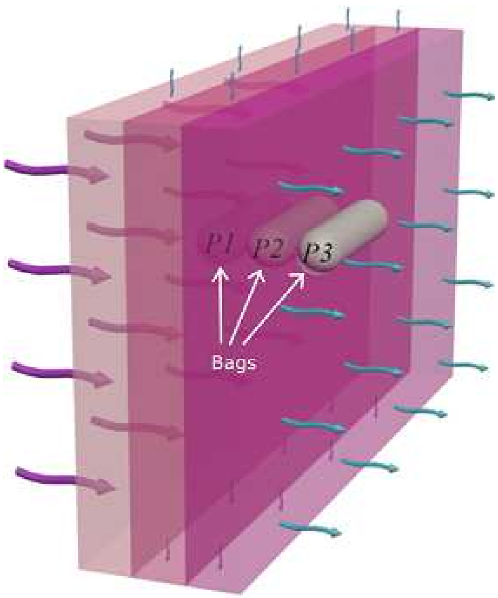

Figure 9: Schematic of location of wood chip bag sample in the drying chamber, P1 – first bag counting from thr air inlet, ect.

3.2 Experimental results

Results of conducted investigations are shown in Tabs. 5 and 6 as well as in Fig. 10. Investigations at the considered pre-prototype dryer were conducted at air velocities lower than those those at the previously discussed laboratory rig. This was caused by low compression ratio of the fan forcing air flow into the dryer. In some cases not all parameters were measured. Due to it, only some information from these measurements are useful to analyze the drying process.

Some terms used in Tabs. 5 and 6. should be explained here. Dynamic pressure at the velocity measure station is measured on the air outflow pipe, Fig. 7. Air velocity in the pipe is calculated using this pressure. Finally, the superficial velocity in the packed bed of wood chips is recalculated form the velocity in the pipe – Superficial velocity of the packed bed. Rows denoted with capital letters *A, B, C* within the field Wood chips samples refer to the measurements of sample bags, Figs. 8, and 9. Bag *A* is located at the air inlet whereas bag *C* at the air outlet. Indexes *A, B,* and *C* are once again used to produce results recalculated from sample bags to entire zones respectively. Figure 10 shows summary of investigations both on the small laboratory rig and on the pre-prototype dryer concerning the total drying rate. The amount of evaporated water is related to the cross-section of the grate and the time of drying. The abscissa refers to the superficial velocity of air. The inlet air temperature was kept at the same level. Some minor parameters like the relative humidity of air were uncontrolled, which leads to data scatter as seen in Fig. 10. However, the predominant characteristic of the process is a linear correlation between the velocity of inlet air and the aforementioned relative mass of evaporated water. Not only the characteristics are linear, but also both sets of points from two different facilities are collinear. That means the drying process was hardly affected by the geometries of the drying chambers.

Laboratory investigations were carried out at the drying medium temperature of about 55 °C. The available drying medium temperature at the pellet/cogeneration plant discussed in introduction section can be likely equal to 140 °C. The drying facility would evaporate then aproximately three times more water from square meter of grate per hour, that is 60 kg/m^2 in real operational conditions.

Table 5: Experimental results (part I).

					Number of measurement								
Parameter			Symbol	Unit	1	2	3	4	5	6	7	8	9
Bulk density of wet wood chips			ρ	kg/m^3	321	265	260	296	250	250	264	220	220
Wood chips moisture content before drying			W	%	51.5	58	51.5	46.9	42.3	43	40	26.8	28.8
Dynamic pressure at the velocity measure station			p_{dyn}	Pa	40	50.5	55	54	50		43.4	50	50
Temperature at the inlet of the drying chamber			T	°C	55	55	55	60	55	55	60	55	55
Temperature at the outlet of the drying chamber			T	°C	34	33.5	35	35.5	34.8	33.4	35.8	33.6	38.3
Air velocity in the pipe			u	m/sek	8.34	9.4	9.8	9.69	9.32	9.8	8.64	9.32	9.32
Superficial velocity of the packed bed			u_1	m/sek	0.51	0.57	0.6	0.59	0.57	0.6	0.53	0.57	0.57
Drying time			t	min	59	70	69	59	65	79	78	75	69
Wood chips samples	A	Sample mass before drying		kg	0.703	0.727	0.964	0.604	0.628	0.628	0.564	0.570	0.462
		Sample mass after drying		kg	0.484	0.578	0.670	0.351	0.421	0.421	0.351	0.427	0.353
		Amount of evaporated water	m_w	kg	0.219	0.149	0.294	0.244	0.202	0.207	0.214	0.143	0.109
		Sample moisture content after drying	W	%	29.5						3.4	2.4	6.8
	B	Sample mass before drying		kg	0.893	0.912	0.867	0.629	0.646	0.629	0.552	0.554	0.452
		Sample mass after drying		kg	0.670	0.848	0.613	0.531	0.569	0.513	0.360	0.439	0.346
		Amount of evaporated water	m_w	kg	0.014	0.069	0.254	0.098	0.079	0.116	0.193	0.115	0.106
		Sample moisture content after drying	W	%	50			37			7.8	7.6	7
	C	Sample mass before drying		kg	0.705			0.594	0.544	0.6713	0.5679	0.5578	0.4407
		Sample mass after drying		kg	0.705			0.591	0.529	0.663	0.499	0.450	0.342
		Amount of evaporated water	m_w	kg	0			0.003	0.015	0.008	0.069	0.063	0.098
		Sample moisture content after drying	W	%	51.5			46.5			1. 37	17.5	8.4
	A	Evaporated water mass in subsequent zones		kg	9.04			11.23			9.69		4.695
	B			kg	0.56			4.19			8.93		4.68
	C			kg	0			0.09			3.11		4.43
Mass of the evaporated water in the drying chamber			m_w	kg	9.6			15.51			21.73		13.8
Drying rate				kg/m^2h	12.2			19.7			20.9		15

Table 6: Experimental results (part II).

					Number of measurement								
Parameter			Symbol	Unit	10	11	12	13	14	15	16	17	18
Bulk density of wet wood chips			ρ	kg/m³	220	227	262.6	264	250	284	296	296	340
Wood chips moisture content before drying			W	%	27.2	29.3	37.7	40.1	40.9	41.7	43.8	47.1	52
Dynamic pressure at the velocity measure station			p_{dyn}	Pa		50	50	30	30	30	55		
Temperature at the inlet of the drying chamber			T	°C	56	55	55	55	55	55	55	55	55
Temperature at the outlet of the drying chamber			T	°C	37.7	32.56	33.21	29.48	24.98	31.15	33.01	32.52	32.65
Air velocity in the pipe			u	m/sek	8.34	9.32	9.32	7.22	7.22	7.22	9.8	7.22	8.84
Superficial velocity of the packed bed			u_1	m/sek	0.51	0.57	0.57	0.44	0.44	0.44	0.6	0.44	0.54
Drying time			t	min	63	49	66	73	91	80	73	74	68
Próbki zrębków	A	Sample mass before drying		kg	0.454	0.519	0.513	0.503	0.651	0.659	0.644	0.658	0.693
		Sample mass after drying		kg	0.347	0.380	0.345	0.330	0.411	0.409	0.386	0.403	0.402
		Amount of evaporated water	m_w	kg	0.106	0.139	0.168	173.9	0.240	0.251	0.258	0.254	0.291
		Sample moisture content after drying	W	%	4.8	3.4	7.3	8.5	6.4		6.3	10.36	17.1
	B	Sample mass before drying		kg	0.479	0.486	0.58	0.569	0.627	0.656	0.666	0.630	0.720
		Sample mass after drying		kg	0.370	0.386	0.412	0.495	0.526	0.594	0.523	0.556	0.679
		Amount of evaporated water	m_w	kg	0.109	0.039	0.136	0.075	0.101	0.062	0.143	0.073	0.041
		Sample moisture content after drying	W	%	5.6	11.1	17.1	31	28		28.4	40.18	49
	C	Sample mass before drying		kg	0.470	0.458	0.546	0.579	0.575	0.619	0.661	0.637	0.722
		Sample mass after drying		kg	0.381	0.432	0.505	0.578	0.570	0.619	0.646	0.638	0.724
		Amount of evaporated water	m_w	kg	0.089	0.026	0.041	0.001	0.005	0	0.015	0	0
		Sample moisture content after drying	W	%	23.3	24.9	32.6	40.1	40.3	41.75	42.5	47.06	52
	A	Evaporated water mass in subsequent zones		kg	4.678	5.583	7.809	8.149	8.353	9.79	10.72	10.36	12.93
	B			kg	4.537	4.216	5.908	3.128	3.65	2.438	5.75	3.1	1.75
	C			kg	3.777	1.19	1.804	0	0.224	0	0.616	0	0
Mass of the evaporated water in the drying chamber			m_w	kg	12.99	10.99	15.521	11.38	12.23	12.22	17.08	13.46	14.68
Drying rate				kg/m²h	15.45	16.8	17.64	11.69	10.08	11.46	17.5	13.64	16.19

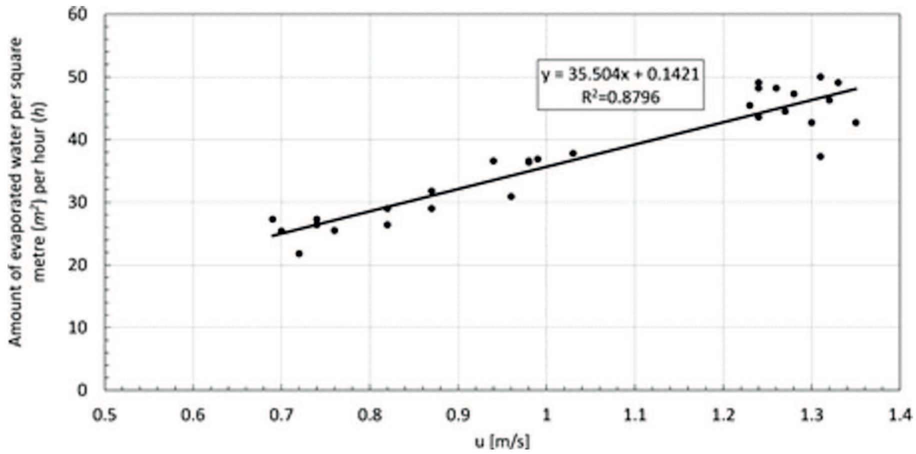

Figure 10: The amount of water evaporated per square meter of the laboratory rig and the prototype dryer per one hour versus inflow velocity of the air.

4 Numerical simulation

4.1 Mathematical modeling

Modeling of the drying process was carried out using the computational fluid dynamic code Ansys Fluent [11]. Among works concerned with cross-flow drying simulation with a boundary between the gaseous phase – air and solid phase – dried matter using Ansys Fluent one can mention the paper of Krawczyk and Badyda [12]. However, this paper deals with a bit more complex situation – the through-flow drying of a porous body. To simulate such a flow, two meshes have to be applied in the same location – one of a solid body and one of the void for the air flow.

Since wood chips make up a collection of particles of different shape and volume, their exact geometrical representation as a simulation mesh is difficult. Currently existing software for geometry and mesh generation are not capable of handling such granular geometries of packed beds. This inconvenience may be by-passed by replacing the actual packed bed geometry by the so called dual cell approach. The technique is implemented in commercial computational code and involves two identical and overlapping grids – one for fluid volume, and one for solid. They simulate pellet and the interstitial void space with a great ease of avoiding laborious geometry creation. However, some drawbacks arise from this approach. The data lost by replacing real geometry with the two meshes must be compensated otherwise. This method requires a few parameters more to quantify flow and thermal properties of the packed bed. Some of these parameters are directly put into Fluent software, the others are represented by means of substitute quantities. A basic set of parameters may be introduced: porosity ε, overall pellet surface A, mean particle surface A_p, mean particle volume V_p, mean hydraulic diameter of a particle d_p. Values of these parameters were obtained from computed tomography.

Figure 11: A bucket of woodchip samples.

Figure 11 shows a bucket with sample woodchips that was subject to scanning. For further extensive computations a control volume of cubic shape with the edge length $l = 0.11$ m was chosen from the center of the bucket.

A few parameters like ε, d_p, A_p, V_p retain their values indenpendently of the sample volume. The others like the woodchips total surface A must be recalculated with respect to the drying chamber volume. Porosity ε is directly input into Fluent software in the porous body tab – *Porous Zone*. Both the diameter and porosity ε are used for calculating flow resistance through the packed bed. Their definitions are enclosed in Ergun's equation and can be found in the software documentation [13] and elsewhere [14–16]. The set of parameters determined with computer tomography is also used to find the convective heat coefficient h and the coefficients of Ergun's equation. These are permeability coefficient α and drag coefficient C. The surface A is put into computational program in an indirect way by means of the so called interfacial area density

$$A_{fs} = \frac{A}{V}\,, \tag{2}$$

which is defined as a ratio of woodchips total surface and bulk density. The latter is the drying chamber volume, Fig. 12.

The last geometry dependent parameter is the convective heat transfer coefficient h. The Whitaker's [17] correlation for packed beds was applied. The required data for calculating its value includes flow cross section surface (0.8 m^2, Fig. 12), cross section circumference (3.6 m, Fig. 12), porosity ε, volume V_p and average particle surface A_p and interfacial velocity u_1.

Other parameters that should be put into program are material constants. The software is equipped with a database for pure substances or mixtures like water, nitrogen, oxygen, air, acetylene-air, carbon-monoxide-air, lignite-volatiles-air, etc., but not for compound solid materials like wood. The required parameters are conventional density ρ_u, specific heat, c_p, and thermal conductivity, λ_p. This set was chosen assuming that the woodchips are made of pine wood. Actually, wood chips supplied to the experiment were unknown with respect to their origin (unknown species). The aforementioned wood conventional density is defined as a ratio of bone-dry wood mass enclosed in 1 m^3 of wood wetted above fiber saturation point to volume 1 m^3. The definition may be found in Glijer, p. 26, [18] together with a table of averaged values for a few species, p. 25.

Two next parameters c_p and λ_p were assessed on the basis of consideration of Simpson and TenWolde [19] with the premise the wood initial moisture content on the dry-solid basis is $X = 108.33\%$. Published correlations [19] depend on several factors, for instance on moisture distribution. And this may be strongly non-uniform within the wood volume and is subject to relatively large measurement errors. Also, the location within the log cross section makes difference if woodchips are from sapwood or heartwood regions. The choice of wood parameters values is a matter of art rather than strict calculations. However, for this modeling the aforementioned considerations did not have a substantial impact.

The complete set of parameters is shown in Tab. 7. All parameters were put into Fluent macros implemented in user defined functions (UDF). Values of ε, λ, c_p, and ρ_u are at hand for using since they are obtained from tomography or tables. A, A_{fs}, d_p, $1/\alpha$, C_2, h are calculated by means of aforementioned correlations. One should notice the heat transfer coefficient h depends on the air inflow velocity u_1.

Table 7: Woodchips packed bed parameters

ε	A	d_p	A_{fs}	$1/\alpha$	C_2	ρ_u	λ_p	c_p	h
							($X = 108\%$)		($u_1 = 0.54$ m/s)
	m^2	mm	1/m	1/m^2	1/m	kg/m^3	W/mK	kJ/kgK	W/m^{2}K
0.4682	486.39	1.74	1836.39	136882320	10436	400	0.153	2	133.24

Extensive simplifications were put upon the modeling. The drying is proceeded according to the first period of drying. The driving force in this period is exclusively the transferred heat that is considered equivalent to the amount of heat needed to evaporate water. So, the process is assumed isenthalpic in nature. It is characterized by a constant drying rate, R, and constant dried mass temperature. The drying rate is implemented into Fluent with the mass source defined in the simulation. This mass is a mass water vapor that humidifies the flowing air up to the saturation state $\varphi = 100\%$. The drying rate R is given by

$$R = \frac{dm_p}{dt} = \frac{hA\,(T_1 - T_w)}{r_w}\ , \tag{3}$$

where r_w stands for heat of water evaporation. Relation (3) is the central point of the considered model. It is of course perceived from the side of the drying air. For the solid mass that is subject to drying, one must define a variable to store water mass that is decreasing in the course of process.

As the air flows through the dried material its temperature decreases towards the saturation temperature T_s. It is equal to the material temperature which in turn is equal to the wet bulb temperature T_w. The T_w temperature may be calculated from the wet bulb temperature equation, for instance Seader *et al.* p. 745 [20]. However, it is one equation with two variables: saturation pressure p_s and saturation temperature $T_s = T_w$. A second equation should be employed to relate T_s and p_s. One may choose equations given by Antoine [21], Arden-Buck [22] or Goff-Gratch [23,24]. No matter which system of two equations is chosen, the output equation is confound with respect to variable T_w. T_w cannot be derived in an explicit way, but with the employment of numerical, iterative methods.

At a particular moment not a whole packed bed volume is dried but only a thin layer. Since the air velocity on the inlet plane is uniform and the initial moisture content X within the volume of the packed bed is uniform too, the process will be one-dimensional with respect to the flow axis. However, since the heat exchange is highly intensive, the temperature drop of the drying air from T_1 to T_w will cover a distance of merely a few or a dozen or so millimeters. So, a drying front is formed. In the course of drying process it moves from the inlet to the outlet of the drying chamber. Further model simplifications are that after the heat and mass exchange front is passed at a particular location, the temperature of solid T_w immediately jumps to the temperature of inflowing air T_1. In a real process the final moisture content X_2 at any location within the packed bed would be correlated to the temperature and relative humidity of air at this site. It is equilibrium moisture content X^*. The assumptions taken for this modelling impose the premised final X_2 value.

4.2 Geometry of the drying chamber of the pre-prototype dryer

The considered geometrical model is based on an existing prototype dryer. The central element of the model is the drying chamber of dimensions 1 m× 0.8 m×0.34 m (width, height, length). So, the encased packed bed is relatively thick. The scheme of geometry and air flow direction is shown in Fig. 12. The partition of the chamber into zones A, B, C is arbitrary and is applied only for the sake of post-processing of the obtained results and to make easier the comparison between numerical simulations and the experiment. Three bags with sample wood chips were placed in experiments in the central part of the packed bed so that each covered one third of the drying chamber length. After the end of the drying process the bags were taken out and a handful of content from each bag was fed into a moisture analyzer. As a result, three discrete values of the moisture content along flow were obtained, each corresponding to the center of the appropriate layer.

The air flows through the void space of the packed bed (through-flow) but in the real drying chamber the inlet and outlet planes are covered with wire meshes to prevent wood chips spilling. This layout is more drying efficient than flow over shelves with the dried medium (cross-flow) since the packed bed is better exposed to the flow and subsequently to the heat and mass transfer.

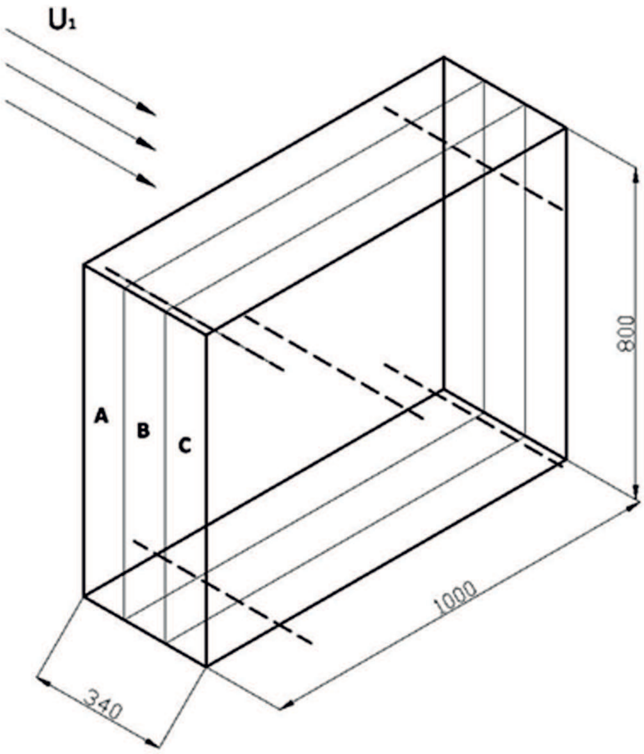

Figure 12: Dimensions of the chamber with the concept of three layers and five axes for postprocessing purposes.

4.3 Boundary conditions and discretization

The analysis of the dryer was limited to the drying chamber which was shaped as a slightly flattened cubic with dimensions 1 m× 0.8 m×0.34 m. Additionally, very short inlet and outlet zones were appended with the same lateral dimensions as the drying zone (chamber). Their lengths amounted, respectively, to $l = 0.02$ m and 0.04 m. So, the overall length of the computational geometry was $l = 0.4$ m, including the drying zone $l = 0.34$ m. Figure 12 shows only the actual drying zone without the inlet and the outlet. Design Modeler software was used to create the geometry.

The mesh was generated taking into account the concept of the dual cell approach. This means there are two overlapping grids in the drying zone with identical numbering of elements. The first mesh, fluid, spans from the inlet to the outlet plane through the inlet, drying and outlet zones respectively. This mesh comprises the flow domain. The other one, solid, present only in the drying zone simulates the woodchips packed bed. The fluid mesh serves for flow computations as well as for water storage. In a real experiment this water is kept in solid body – woodchips. However, dual cell approach requires that all fluids and also their sources are defined on the fluid mesh. Thus, other flow and heat exchange parameters like porosity ε, interfacial area density A_f that introduces in an indirect way heat exchange area A, permeability α and inertial loss C_2 coefficients and, finally convective heat exchange coefficient h are set on this mesh. The fluid mesh also comprises vapor stream source R that can be treated from the air point of view as humidification but for solid is equivalent to drying. Water for the stream is stored in the fluid mesh cells by means of pre-defined memory function C_UDMI implemented in the UDF code. The solid mesh conveys only the solid temperature that in the first period of drying is equal to the wet bulb temperature T_w.

The mesh (fluid, solid) is structural with the total number of cells 6 112 116 in the fluid mesh. This includes 2 874 510 cells in the drying zone both in the overlapping parts of fluid and solid meshes. The grids were prepared carefully taking into account the expected high intensity of heat exchange, the flow parameters gradients would be considerably large. For instance, the drop of inlet temperature from T_1 to the saturation temperature T_w would cover only a distance of several millimeters. Considering results of quantities that are variable only along flow axis z, one should have at least a few points on the curves in the drop zone. In the course of test computations a grid that fulfils the grid independence conditions was elaborated. In this grid the cell distribution in the drying zone follows the pattern: lateral edges are divided into 123 elements, the edges along the z-axis are divided in 190 elements. In order to easily produce 1D results, five axes for data show were chosen on the mesh. The first one is the central axis z, the remaining four are closer to the corners, see Fig. 12.

Among parameters constituting boundary conditions one should mention air velocity u_1 at the inflow plane of the packed bed, inflow air temperature T_1, inflow air mass humidity Y_1, initial and final packed bed moisture contents X_1 and X_2. Mass humidity Y_1 should be recalculated into mass fraction as this is the quantity required by Fluent software. That is performed automatically by an appropriate procedure of the user defined function code. In the course of computations, a dry-solid moisture content X was used, however, to make the comparison with experimental data easier, a wet-solid moisture content W was also shown. Definitions of X and W and dependencies are given by

$$X = \frac{m_w}{m_s} , \tag{4}$$

$$W = \frac{m_w}{m_w + m_s} , \tag{5}$$

$$X = \frac{W}{1 - W} \tag{6}$$

$$W = \frac{X}{1 + X} , \tag{7}$$

where m_w is the mass of water, and m_s – bone-dry wood chips mass. The set of boundary conditions is shown in Tab. 8.

Table 8: Boundary conditions.

u_1	T_1	Y_1	X_1	X_2	W_1	W_2
m/s	°C	g/kg	%	%	%	%
0.54	60	0	108.33	20.63	52	17.1

4.4 Numerical method

Previously mentioned commercial Ansys Fluent software was used in simulations. The package has an ability to deal with quite a wide scope of fluid flow problems. That is, one can remark that it is not equipped with the drying models. These should be implemented by the user. First, appropriate codes should be written in general-purpose programming language C language, then compiled by means of graphical interface and finally linked as a library.

Since the process is unsteady, the model chosen for computations was transient. It takes into account that during drying the quantity of water stored in a solid body is decreasing and the boundary between dried and undried zones is traveling downstream with the flow. Among the available Fluent models, energy and species – species transport models were applied. The former enables thermal computations, the latter implements gas mixtures. The flow was assumed laminar.

The PISO (pressure implicit with splitting of operator) algorithm was applied for solving Navier-Stokes equations, since the scheme is well suited for unsteady flows and large time steps. For gradient discretization least squqres cell based was chosen. Second order uUpwind scheme for pressure, momentum, water content and First Order Implicit for time derivatives were respectively used in discretization. The time step was set constant at $t = 0.2$ s. Twenty iterations for a time step were retained.

The core elements of the simulation drying model were: water vapor flux into air and water storage in computational mesh with its subsequent depletion during the process. Water quantity was implemented into the fluid mesh by means of predefined memory function C_UDMI. The initial quantity was set in the DEFINE_INIT macro. Vapor stream R was rendered by the DEFINE_SOURCE macro. In this macro as well as in DEFINE_EXECUTE_AT_END calculation of water remaining in the mesh (C_UDMI) was performed. That was the basis for calculation of next variables including wood moisture content X (dry-solid basis). Initial conditions were specified in macros DEFINE_PROFILE. Also the temperature T_w of the wet packed bed set for *solid* mesh was put in one of these macros. If in a particular mesh cell the assumed final moisture content X_2 is achieved, the calculations of the vapor flux in the macro DEFINE_SOURCE were be stopped. At the same time the temperature T_w of the cell would be discretely increased to the value of the air inlet temperature T_1 by means of one of DEFINE_PROFILE macros. The very T_w temperature was once calculated at the beginning of simulation in the DEFINE_INIT macro. The same macro was used for several other auxiliary calculations and tests, for instance for checking of fluid and solid meshes overlaping. All macros were gathered in one source file. Some of them performed independent calculations fully separated from other macros calculations. Other macros performed computations with data exchange between one another by means of C language variables or UDF memory functions C_UDMI.

5 Results of computational model and comparison with experiment

The unsteady drying computations were carried out till the drying time of $t = 68$ min was accomplished. It is equivalent to the experimental case denoted as 18, Tab. 6. Since the flow geometry considered in simulation is extremely simplified, without air inlet and outlet elements like flexible pipes, diffuser, confusor, it is clear that flow parameters as well as porous packed bed parameters will be cross-section uniform. Variations take place only along the flow axis z. For illustrative purposes of 2D characteristics of the process, the temperature distribution along five axes, as selected in Fig. 12, is shown in Fig. 13.

Apart from the cross-section uniformity of temperature distribution, a rapid temperature drop from $T_1 = 60\,^{\circ}\mathrm{C}$ to $T_w = 20\,^{\circ}\mathrm{C}$ is visible. That confirms earlier premises that the porous packed bed with the through flow is characterized by a high intensity of heat exchange. It may be partially accounted for a large heat exchange coefficient h. This, in turn, is owing to a very small mean diameter of an equivalent woodchips particle. Indeed, the largest tribute to the number of packed bed particles holds the smallest size – dust, in principle. Irrespectively of large value of the heat exchange coefficient, a crucial tribute to the huge heat exchange intensity belongs to heat exchange area A. This is due to a huge the number of particles. As a result it is not possible to dry woodchips on an entire length of the packed bed. Instead, a thin layer of heat and mass transfer is formed of the width of about l = 5 mm. This thin layer may be described as the drying front. It is easily observed in the experiment. Wood wetted above fiber saturation point X = 26–30% may be obtained only by immersing in water and is perceived by sight as wet. The layer between dried wood chips $X \approx 20\%$ and still undried X = 108% is so thin that it is clearly visible through a transparent wall of the laboratory rig as a boundary between wetted and dried zones.

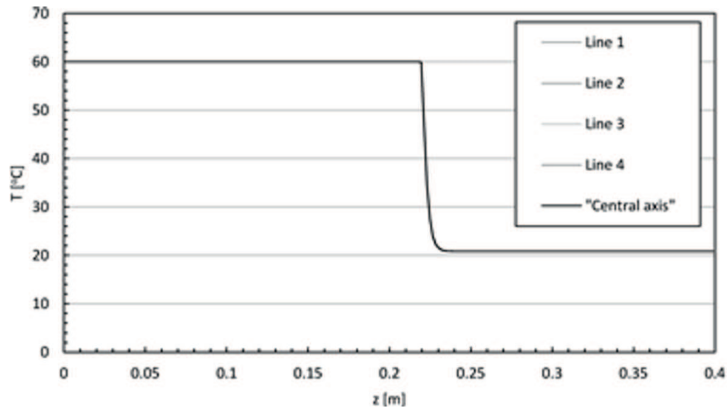

Figure 13: Flow parameters uniformity shown on the temperature distribution along five axes at an instant t = 68 min.

Drying front shifting along the flow was observed in the laboratory rig with its transparent walls, Fig. 5. An equivalent situation in numerical computations is shown in Fig. 14, revealing the moisture content distribution X frozen at 68th minute of numerical simulation of the drying process.

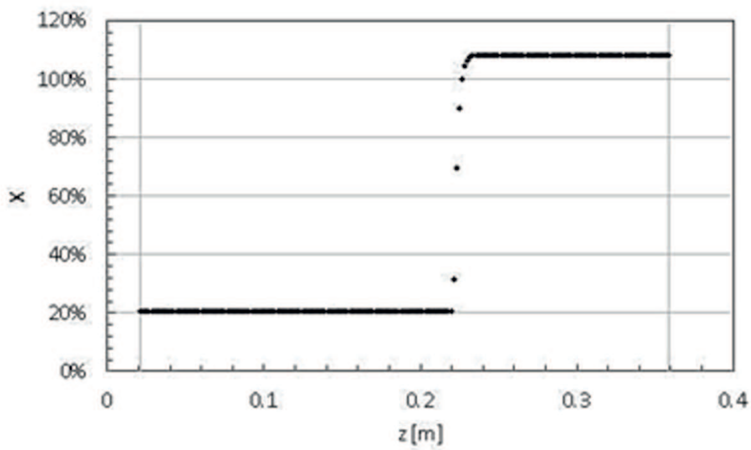

Figure 14: Drying interface in numerical computation on example of moisture content X at an instant $t = 68$ min.

Measurements of moisture content were confined to discrete values, i.e., three points. Each was averaged for one third of the chamber depth of the prototype dryer. Similarly, the part of computational mesh containing the drying zone was divided in three layers for averaging purposes. The scheme of division is depicted in Fig. 12. Computational and experimental results are tabulated in Tab. 9 and gathered in a graphical form in Fig. 15. Essentially, the zone A that is closest to the air inlet is dried to the level $X = 20\%$ met in experiment whereas zone C remains undried, at the initial level $X = 108\%$. A substantial difference of moisture contents occurs in zone B. Numerical simulation yielded $X = 39\%$, but the experiment gave $X = 96\%$. So, after $t = 68$ min of drying in experiment zone B is only slightly dried, whereas the computations indicate a substantial degree of dryness.

This means that drying in simulation was faster than in the experiment. One possible explanation is that the wood chips mass in the zone B was underestimated in experiments. This mass is not weighed directly, but recalculated on the basis of the mass and volume of measurement of the sample bag.

The air inlet temperature in simulation was somewhat higher than in experiment, 60 °C vs. 55 °C, but the deviation seems mostly owing to drying model simplifications – missing the second period of drying. The drying rate R in the first period is constant and larger than in the second period. Moreover, the drying rate in the second period is decreasing in the course of process.

A few premises relating to the first and the second period of drying should be considered. Firstly, the first period of drying is wholly enclosed in the moisture content range of unbound water. Secondly, the initial moisture content of wood chips was relatively high, $X = 108\%$. Thirdly, the fiber saturation point for wood equaled to $X^* \approx 30\%$ marks off the unbound and bound moisture. Fourthly, critical moisture content X_c marks off the first and the second period of drying. Its value is not tabulated nor explicit relations for X_c are widespread. This value is not less than X^*, and at the first approach may be perceived as $X_c = X^*$. Taking into account the above considerations it seemed natural to confine the drying model entirely to the first period. Since the required final moisture content was set to $W_2 = 20\%$ ($X_2 = 25\%$), initial moisture content was $X_1 = 108\%$, the amount of evaporated water assigned to the first period equaled to $\Delta X = 108 - 30 = 78\%$ (pp). Only the remaining $\Delta X = 30 - 25 = 5\%$ moisture is bound moisture. It was subjected to the first period of drying too, according to the assumed simplifications. However, the discrepancy of final moisture contents of the central zone B can't be rather explained by 5% of bound moisture assigned to the first period of drying. Careful analysis should be devoted to the critical moisture content X_c. If its value was higher in the simulation, the second period of drying couldn't be avoided. Thus more moisture to be evaporated would be left for the second period characterized by slower drying rate R.

The matter of critical moisture content for wood species is rather dim and far from conclusions. Ananias *et al.* [25] obtain an averaged value of the critical moisture content. They show that X_c depends on all of the studied operating parameters and that they are in a range of absolute wood moisture content between 56.3 and 138.3%. The latter exceeds the initial moisture content in the present simulation. To make matters worse, Ananias *et al.* [25] indicate the X_c values cannot be known a priori.

Table 9: Comparison of experimental and computational results.

	t	W_1	W_{2A}	W_{2B}	W_{2C}	Δm_w	Δm_{wA}	Δm_{wB}	Δm_{wC}	X_1	X_{2A}	X_{2B}	X_{2C}
	min.	%	%	%	%	kg	kg	kg	kg	%	%	%	%
Experiment	68	52	17.1	49	52	14.68	12.93	1.75	0	108.33	20.63	96.08	108.33
Calculations	68	52	17.04	28.11	52.00	29.59	16.66	12.93	0	108.33	20.54	39.10	108.33
Difference	0	0	0	0.4	0	-1.0	-0.3	-6.4	0	0	0	0.6	0.0

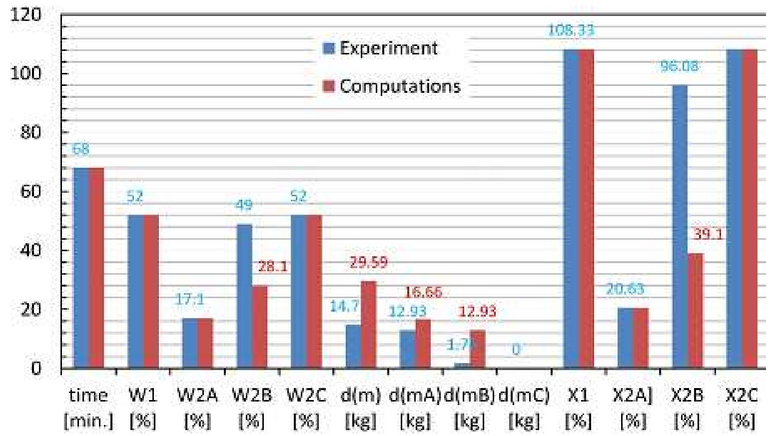

Figure 15: Comparison of experimental and computational results.

6 Conclusions

Results of experimental and numerical investigations of wood chips drying are described in the paper. Experiments were carried out on two test facilities: a small laboratory rig and a larger pre-prototype dryer. Both facilities were through-circulation convective dryers with slightly heated air as a drying medium. Numerical analysis of the drying process was conducted using the commercial Ansys Fluent program with self-written procedure simplementing drying principles.

The experimental investigations show that the relative amount of evaporated water from the packed bed of wood chips is a linear function of the incoming superficial velocity of air. The relative amount of evaporated water is the drying rate and should be understood as water mass that evaporated from one square meter of the dryer grate during one hour. Velocity range contained between u_1 = 0.44 m/s and 1.36 m/s, whereas the drying rate between $R = 10$ kg/m^{2}h and 50 kg/m^{2}h. Lower velocities were achieved at the pre-prototype dryer, $u_1 = 0.44$–0.6 m/s, higher at the small laboratory rig, $u_1 = 0.68$–1.04 m/s. Appropriately, drying rates enclosed in ranges $R =$ 10–20 kg/m^{2}h and 20–50 kg/m^{2}h. Both sets of results are linear, and though obtained from a different apparatus are colinear too. The temperature of inlet air in the pre-prototype dryer was kept mostly at $T_1 = 55\,^{\circ}$C. The velocity of $u_1 = 0.6$ m/s was found feasible for maintaining a quasi-stationary packed bed.

Because of its transparent tube wall, some qualitative data was taken from experimental investigations upon the small laboratory rig concerning dried and undried layers of wood chips. In the course of process a thin border between the two layers was observed to travel along the flow. It leaves behind the dried layer with the still wetted layer remaining ahead. The phenomenon was best visible on the packed bed of sawdust because of its smaller particle sizes.

Computational fluid dynamic software was used to carry out a simulation of woodchips convective drying with through-flow. Elements of the drying process that were missing in the original package Fluent were supplemented in the form of self-written UDF functions. The codes encompass relationships for the first period of drying. The data taken for numerical computation was chosen from one of the most moisturized experimental series ($W = 52\%$, $X = 108\%$) with the same drying times, inlet superficial velocity and nearly the same inlet temperature ($T_1 = 55\,^{\circ}$C) in experiment, $T_1 = 60\,^{\circ}$C in simulation). The packed bed parameters referring to particles size were taken from computer tomography. Since the predominant water mass to be evaporated from wood chips was the unbound water it seemed natural to confine computations to the first period of drying as a first approach.

Theoretical computations reveal existence of a thin layer where the almost entire process of drying is concentrated. This layer travels along the flow in the course of process leaving dried wood chips behind. It is consistent with the observations in experiments on the small laboratory rig.

The same drying times applied both in simulation and experiment yielded closely related moisture contents X in the entire packed bed. The convention of division of the packed bed on three layers was the same as in the experiment. The first layer A counting from the air inlet was dried to the same level as in the experiment, the last C one remained undried that is also experimentally confirmed. Discernible differences appeared in the central layer B that was slightly dried in the experiment while it was much drier in the simulation. That means the drying rate in the simulation is faster than in experiment. Mostly it is due to the missing second period of drying in the simulation. The drying rate in the first period is constant and higher than in the second period. More investigations are needed to include the second period of drying in the numerical simulation.

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