EXPERIMENTAL INVESTIGATION OF PRE-DRYING DATA FOR SOME MEDICINAL HERBS IN FORCED CONVECTION

by

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The special active agent content of herbs makes them suitable for healing and health preservation. The key element in the processing of herbs and spices is drying. Before drying, the medicinal plants should be stored under appropriate conditions to avoid deterioration of quality where one of the possible methods is pre-drying with ambient air. This work defines the determination of main operational parameters at forced convection drying with ambient air like drying rate, volume decrease, maximum drying air velocity, and porosity for various medicinal plants (common yarrow – Achillea collina, giant goldenrod – Solidago gigantea, wormwood – Artemisia, walnut leaf – Juglandis folium, wild carrot – Daucus carota). To determine the drying rate, a convective dryer was used where the average drying rate of common yarrow and wild carrot were the highest followed by giant goldenrod, walnut leaf and wormwood. Measurements were made on a pilot plant fluidized bed dryer to determine the volume decrease and the maximum drying air velocity. The volume decrease was determined as a function of time and moisture content. It was found that the maximum drying air velocity for each medicinal plant was between 1.8 and 2.2 m/s. In addition, for each herb the porosity was measured by an air pycnometer.

Key words*: herb, drying rate, moisture ratio, volume decrease, porosity, drying air velocity*

Introduction

The role of medicinal plants in therapy has changed throughout ages, closely linked to the state and the level of the therapy. While synthetic medicines have undoubtedly played an important role in improving human living standards, herbal medicines have been revalued in the field of therapy. Instead of focusing on curing an illness, people these days strengthen the immune system of their bodies thus making themselves more resistant to the diseases [1]. Shaarschmidt [2] made a review on product standards for general physical and chemical specifications which are relevant to product quality and chemical characteristics in the case of culinary herbs and spices. Within this, the emphasis is on the dried culinary herbs and spices at global and EU level.

Their special active agent content makes herbs suitable for healing and health preservation. A significant number of medicinal plants are pharmaceutical raw materials which can be extracted from the active agent by various procedures. The aim of medicinal plants processing is turning herbs into some form of drug, pure active agent or medicament. Primary processing involves collecting or harvesting, cleaning, drying, qualification*, etc.* Not all parts of medici-

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nal plants contain the same quality and quantity of active agents: that is why different parts of herbs are suitable for drug manufacturing. Fresh plant parts are often very vulnerable and can become worthless and discolored during harvesting. Therefore, storage devices for harvesting should be selected by considering the vulnerability of the plant species and parts. The moisture content of harvested plants is generally very high around 60-80%. If the moisture content is not significantly reduced, it enables the maturation of harmful biological processes. Because of this, valuable active agents of herbs can be destroyed and the external properties of drugs can become unfavourable. The fundamental requirement to prevent harmful processes is the reduction of moisture content as quickly as possible. The moisture content of medicinal plants must be 10-14% at the end of the drying process. With this moisture content most drugs can be stored for a prolonged period of time without damage to the plants [3].

The drying of medicinal plants nowadays is a relevant topic and since drying is one of the most energy consuming heat and mass transfer process, reducing the amount of required energy and drying time are important issues for drying technology. A number of publications can be found in the literature in which the researchers dealt with the drying of medicinal plants and the effect of each drying method on them. The review of Babu *et al.* [4] contains possible drying methods for leaf drying with their advantages, disadvantages, methods and equipment. They also presented the nutrient preservation and the different mathematical models. Some researchers compared different drying methods by examining their effect on the various ingredients like phenols, antioxidants [5, 6], essential oil content and color [7]. Furthermore, the variation of drying parameters for different drying methods was also investigated [7-9]. The case of an indirect solar dryer integrated with a phase change material [10], a solar collector using simultaneously biogas fuel to heat the drying air [11], and a heat pump operated dryer [8] were also investigated for medicinal plants drying.

Aktas *et al.* [12] analysed the drying characteristics of mint leaves in a new cylindrical form of drying chamber at low drying air temperature while emphasizing on energy analysis. They determined that the drying chamber, with three stainless steel cylinders in circular nested form, has a positive effect for drying technology. This system had some advantages such as: drying of product by accessing a uniform air-flow and preventing spread of lightweight samples like mint leaves over the drying system.

During the processing of medicinal herbs at daily operations bottlenecks can easily occur when large amounts of herbs – above the drying capacity – are transported to the factory for reasons including various plants' unexpected simultaneous flowering, weather emergencies, extraordinary collecting*, etc.* The extent of the dryer capacity defines the processing capacity of the factory. Therefore, incoming plants should be stored under appropriate conditions prior to final processing. This is especially important if the plants have high moisture content, for example if they have been exposed to rain before or during harvesting. In this case, the active agent content and enjoyment value of the herbs can also be reduced during shorter storage. One possible way to prevent this is by pre-drying herbs with ambient air. The low moisture content of medicinal plants required for storage can be achieved only by applying drying equipment under certain climatic conditions. Pre-drying not only protects medicinal plants from damage during storage but also reduces the energy demand for drying by hot air.

Proper design and sizing of pre-drying equipment operating with ambient air requires the determination of the characteristics of the material to be dried and the various drying parameters like the drying rate, the volume decrease, the maximum drying air velocity and the porosity. The aim of our work is to describe the measurement methods and publish data for these properties of the five different medicinal herbs.

Material and methods

In the course of our research the characteristics of five different herbs were determined. The measuring methods were also described for the empirically determined values.

Experimental material

In the experiments the investigated plants consist of common yarrow (Achillea collina), giant goldenrod (Solidago gigantea), wormwood (Artemisia), walnut leaf (Juglandis folium) and wild carrot (Daucus carota) which can be seen in fig. 1.

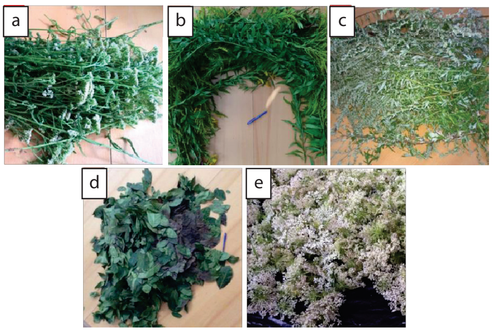


Figure 1. The investigated medicinal plants; (a) common yarrow, (b) giant goldenrod, (c) wormwood, (d) walnut leaf, and (e) wild carrot

The common yarrow grows 20-80 cm tall and has no branches except near the top. The length of leaves vary between 8-13 cm with many leaflets on each side of the midrib and these are further divided into smaller leaflets. Flower heads are arranged in large, compact clusters at the top of the stem [13]. Common yarrow is an excellent antiphlogistic with a wound healing and wound constricting effect. It was used to break a fever by increasing perspiration and its tea was used to cure stomach disorders [13, 14]. The giant goldenrod is 50-220 cm tall and largely unbranched, except at the apex where the flowering stalks can be found. The size of leaves alternate from 8-13 cm long and 0.8-1.7 cm across. The central stem ends in a panicle of yellow flower heads up to 3 cm long and 3 cm across [15]. Giant goldenrod is effective against kidney stones and high blood pressure. The leaves and blossoms are a valuable remedy in the treatment of all kinds of hemorrhages [16]. Wormwood is 50-100 cm tall and has grey-green or white stems covered with fine hairs. The yellowish-green leaves have glands that contain resinous particles where the natural insecticide is stored. Wormwood is often used as a digestive stimulant and promotes healthy liver function as well [17]. The walnut leaves, about 30-60 cm long, consist of 15-23 leaflets born on very short stalks [18]. Walnut leaves clean the blood, correct the stomach and cure indigestion [19]. The mature plant of wild carrot is 60-150 cm tall. Alternate leaves occur sparingly along the central stem. Its flower is corolla regular, white-yellowish-reddish with 4-7 mm wide petals [15]. Wild carrot is primarily used for vision correction, but the core of it is an appetizer and has a positive effect on digestion. It is used for urinary tract problems including kidney stones and bladder problems [20].

As shown in fig. 1 only some of the relevant parts of the plants were examined: in the case of common yarrow, giant goldenrod and wormwood the whole plant was used expect for the roots. For the walnut leaf only the leaves with a short stem were used, whereas for the wild carrot the flower with a short stem was examined.

Preparation and physical properties of the materials

Before the measurements, the herbs underwent various preparation procedures. To determine the minimum fluidization velocity and the porosity, the herbs had to be shredded to pieces smaller than 50 mm so that they can be placed in the apparatus. Figure 2 shows the medicinal plants after shredding.

Before and after each measurement, the moisture content of the plants was determined. The initial moisture content was determined by sampling where the initial weight of the

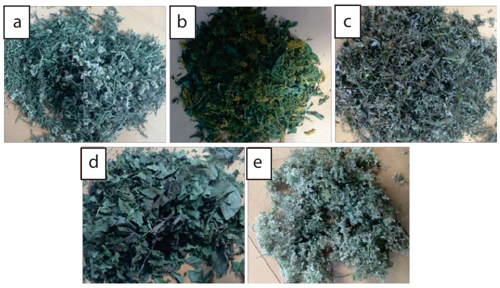


Figure 2. The investigated medicinal plants after chopping up; (a) common yarrow, (b) giant goldenrod, (c) wormwood, (d) walnut leaf, and (e) wild carrot

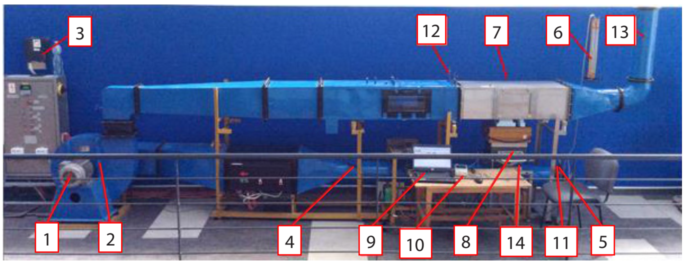
small sample was measured, then the sample was dried out to constant weight at 105±5 °C. After the required drying time the weight of the sample was measured again to obtain the weight of the dry material. The same method was used to determine the final moisture content of the material after drying. Mass measurements were performed by a 0.001 g precision Sartorius LA1200S scale.

Experimental methods

The following section discusses the measuring method and the experimental apparatuses which were used during the measurements [21].

Determination of drying rate and moisture ratio by convective dryer

During the measurements the equipment installed at our department was used, the apparatus can be seen in fig. 3 [22]. The measurement begins by filling the herbs into the drying chamber – 7. First, the initial weight of herbs is measured by a scale and the initial height of plants is determined by a tape measure. While the herbs' initial moisture content is determined by small sample testing, the weight of the sample is measured by a high accuracy scale.



Description	Measured quantity	Measuring range, accuracy
6 U-tube manometer	Pressure difference on the orifice plate	0-480 mm, ±1 mm
7 Drying chamber scale	Height of material	0-320 mm, ±5 mm
8 Sartorius Signum1 scale	Weight of material	0-65 kg, ±1 g
11 ALMEMO D6 FHAD 46-4x digital temperature and humidity sensor	Relative humidity and temperature of ambient air	–20-80 ˚C and 10-90% ±0.01 ˚C and ±1.8%
12 T-type thermometer	Temperature of drying gas	–200-400 ˚C, ±0.1 ˚C

Figure 3. Convective dryer and used instruments during the measurement; *1 – electric motor, 2 – centrifugal fan, 3 – frequency converter, 4 – butterfly valve, 5 – orifice flow meter, 6 – U-tube manometer, 7 – drying chamber, 8 - scale, 9 – analysis software, 10 – data logger, 11 – measuring device for temperature and absolute humidity of ambient air, 12 – measuring device for inlet air temperature, 13 – outlet pipe, 14 - elevator*

The drying chamber is placed on the scale – 8 and raised from the bottom into the dryer by the elevator – 14. Later the centrifugal fan – 2 is started that is driven by an electric motor – 1 and the flow rate can be modified by the frequency converter – 3, and the butterfly valve – 4. A *U*-tube manometer – 6 measured the pressure difference on the orifice plate – 5 from which the air velocity can be calculated. During the measurements the following values are registered by the data logger – 10, temperature and absolute humidity of ambient air by a humidity sensor – 11, inlet temperature of drying gas by *T*-type thermometer – 12, and the varying weight of plants by the scale. The measured values are registered with one minute sampling by the software – 9. Each measurement takes about six to eight hours depending on the herb. The humid gas leaves the system through an outlet pipe – 13 to the environment. The measurement ends by stopping the fan and taking out the drying chamber from the dryer. The final weight and final height of plants are measured by the same method and instruments as the ones used in the measuring of the initial values. Finally, the herbs' final moisture content is determined by a small sample testing.

During the drying process the electrical heater of the convective dryer was not switched on, so the temperature of the flowing gas was equal to the ambient air temperature. The velocity of drying gas was chosen at 0.5 m/s based on previous research [1]. This air velocity resulted in a sufficient drying rate with relatively small energy consumption. Furthermore, this velocity has to be below the minimum fluidization velocity in order not to carry away the herb parts by pneumatic transport.

An average drying rate can be determined from the measured values, which is related to the volume of material, valid at a given moisture content range, temperature and absolute humidity of drying air:

$$N_{\mathrm{V}} = \frac{\Delta m_{\mathrm{w}}}{t V_0} \tag{1}$$

where Δm_{w} [kg] is the weight loss of the studied medicinal plants which is the moisture loss during drying, V_0 [m^3] – the initial volume of the herbs, and t [s] – the drying time.

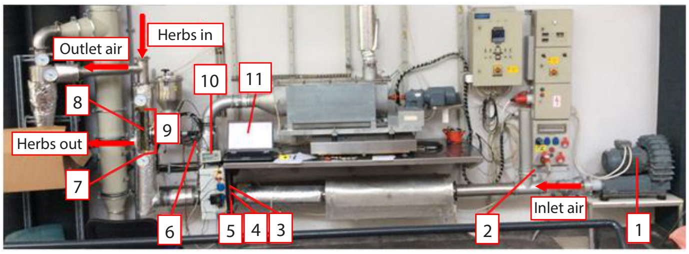
The drying process can be characterized by drying rate curves where the moisture ratio is plotted as a function of time. The moisture ratio can be determined:

$$MR = \frac{X - X^*}{X_0 - X^*} \tag{2}$$

where X [$\mathrm{kg_{water}/kg_{dry\ product}}$] is the current moisture content of herbs, X_0 [$\mathrm{kg_{water}/kg_{dry\ product}}$] – the initial moisture content of herbs, and X^* [$\mathrm{kg_{water}/kg_{dry\ product}}$] – the equilibrium moisture content of herbs which is neglected in this case [23]. Drying rate was not only investigated for different medicinal plants at constant air velocity but at different air velocities for a given plant.

Determination of minimum fluidization velocity and volume decrease by fluidized bed dryer

The measuring equipment – a pilot plant fluidized bed dryer – is located at our department too and fig. 4 shows this equipment [24]. The air-flow needed for the examination of the phenomenon of fluidization is provided by a blower – 1 where the flow rate can be modified by a knife gate valve – 2, and can be measured by an orifice flow meter – 3 using the pressure difference. Before the measurement, the studied plants are charged through an upper opening into the central part of the measuring system which is a vertically positioned chamber – 8 with 100 mm diameter. During the measurement the differential pressure of the chamber – 9, the inlet gas temperature – 7, the differential pressure on the orifice plate – 5, and the absolute humidity of the ambient air – 6 are measured. The measured values are registered using a self-developed software – 11 by a data logger – 10.



Description		Measured quantity	Measuring range, accuracy
4	T-type thermometer	Air temperature at orifice plate	–200-400 °C, ±1 °C
5	Differential pressure transmiter DPS, Ahlborn	Pressure difference on the orifice plate	0-1000 Pa ±10 Pa
6	ALMEMO D6 FHAD 46-4x digital temperature and humidity sensor	Relative humidity and temperature of ambient air	–20-80 °C and 10-90% ±0.01 °C and ±1.8%
7	T-type thermometer	Temperature of the inlet air	–200-400 °C, ±0.1 °C
8	Drying chamber scale	Height of material	0-300 mm, ±5 mm
9	DATCON Differential pressure transmitter	Pressure drop of the drying chamber	0-2000 Pa ±10 Pa

Figure 4. Fluidized bed dryer and used instruments during the measurement;
1 – blower, 2 – knife gate valve, 3 – orifice flow meter, 4 – measuring air temperature at orifice plate, 5 – measuring pressure drop of orifice plate, 6 – measuring absolute humidity and temperature of ambient air, 7 – measuring inlet air temperature, 8 – drying chamber, 9 – measuring pressure drop of chamber, 10 – data logger, 11 – analysis software

The measurement begins by chopping the medicinal plants to help their placement in the chamber. The chopped plants are fed manually through the upper opening into the chamber and the initial height of plants is measured by the scale on the wall of the measuring equipment. Before measuring, the herbs' initial moisture content is determined by small sample testing. The next step is starting the blower while the knife gate valve is completely open. The air velocity is raised by gradually closing the knife gate valve while the measured values are registered with 10 seconds sampling by the software, including the differential pressure and air temperature at the orifice plate, the differential pressure of the chamber, the inlet temperature of air and the absolute humidity and temperature of the ambient air. The measurement is continued until the edge of the fluidized state is reached which is the minimum fluidization velocity where the herbs are just not yet fluidized. At this point the knife gate valve is opened, the blower is stopped and the plants are removed through the opening on the left side of the chamber from the system.

The fluidized bed dryer was also used to determine the volume decrease. The measurements required the same preparations as described previously, then starting the blower while the knife gate valve is completely open. During the measurements, the measured values are the same parameters as the ones registered by the data logger in the determination of the minimum fluidization velocity but the sampling time is 1 minute. In addition, the height of the plants is recorded every half hour during drying. The measurement is continued until the variation of the height of the material is negligible. Then the blower is stopped and the plants are removed through the opening on the left side of the chamber from the system. After the measurement the herbs' final moisture content is determined by small sample testing.

During measurements the height of material was recorded in every half hour from which the volume of the material was determined:

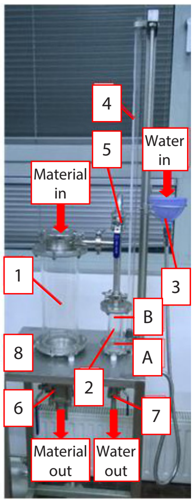
$$V = H\frac{d_{\mathrm{ch}}^2\pi}{4} \tag{3}$$

In order to simplify the comparison of measurement results a percentile decrease was calculated at each measuring point:

$$V_{\%} = \frac{V}{V_0}100\% \tag{4}$$

Determination of material density and porosity by air pycnometer

During the drying process, the maximum bed height is also an important parameter to be determined, because the thicker the bed is, the more difficult it is to ensure a uniform quality at the end of the operation. In order to influence product quality, the goal of this investigation is to determine drying parameters, including – in addition those mentioned before – bulk density and porosity which is calculated from the former. Knowledge of porosity contributes to the determination of the flow resistance of the bulk of plants and of volume decrease during drying. In order to measure herb porosity, an air pycnometer was available, the arrangement is shown in fig. 5.



Description	Measured quantity	Measuring range, accuracy
4 Measuring tube scale	Pressure drop in the vessel	0-920 mm, ±1 mm
8 Manometer	Atmospheric pressure	79.5-106.5 kPa, ±0.1 kPa

Figure 5. Air pycnometer and used instruments during the measurement; *1 – measuring vessel, 2 – compression tank, 3 – funnel, 4 – measuring tube, 5, 6, and 7 – ball valve, 8 – measuring atmospheric pressure*

Before the measurement, the moisture content was determined with reference to dry matter by using small samples for each herb. In the course of the measurement, the bulk density of the material was measured first, afterwards the material density of the plant was specified by the air pycnometer. As long as the density of a granular material is a constant value, its bulk density will vary between two limit values as a consequence of the arrangement of the bulk of material. During measurement, material of a given volume was filled in the measuring vessel, followed by weight measurement. The plant weight is known by a 0.001 kg accuracy scale, its volume can be measured indirectly by determining the volume of air displaced by the herb. If the volume of air enclosed in the measuring instrument is measured without the material placed in, and then together with the material placed in, the difference of the two air volumes measured will yield the plant volume.

When measuring the volume of air enclosed in the measuring instrument, ball valve – 6 and 7 were closed on the empty measuring instrument and ball valve – 5 was left open. The sealing ring and the cap was placed onp – 1 of the measuring vessel, fixed by a triclamp binder. Water was filled in the funnel – 3 until the water level in the compression tank – 2 reached mark *A*. The funnel was first in the bottom position where the water level was in line with mark *A*. After precise level adjustment ball valve – 5 was closed, thereby the air was locked in the system. By lifting the funnel and constantly supplementing the water running out of the funnel, the water level in the compression tank was set to mark *B*. The water level can be read from the scaled measuring pipe – 4. The water can be drained from the system first by opening tap – 7 then tap – 5. The course of measurement with the material placed in corresponds to the aforementioned, with the difference that the material of known mass is placed in the measuring vessel before fixing the cap.

By definition, porosity means the proportion of the volume of intergranular space to the total volume [25]:

$$\overline{\varepsilon} = \frac{V_{\mathrm{H}}}{V + V_{\mathrm{H}}} \tag{5}$$

This highly depends on the shape of granules: porosity may decrease if the set of granules consists of particles of different sizes and shapes arranged irregularly whereas porosity may increase if the set consists of stringy or shell-shaped granules.

In order to determine porosity, either volumes or densities need to be measured, since eq. (5) can also be stated with densities:

$$\overline{\varepsilon} = 1 - \frac{V}{V + V_{\mathrm{H}}} = \frac{\dfrac{V}{m}}{\dfrac{V + V_{\mathrm{H}}}{m}} = 1 - \frac{\dfrac{1}{\rho}}{\dfrac{1}{\rho_{\mathrm{H}}}} = 1 - \frac{\rho_{\mathrm{H}}}{\overline{\rho}} \tag{6}$$

Results and discussion

The measurements were conducted and the measurement results were evaluated that can be read in this section. The sophisticated instrumentation and reliable measurement background made it possible to perform long-term drying measurements at a certain settings only once.

Drying rate and moisture ratio

During measurements for the determination of drying rate, the parameters described in section *Determination of drying rate and moisture ratio by convective dryer* were registered. Table 1 shows initial data and measurement results at various medicinal plants where the measurement error of the drying rate also can be seen.

During measurements common yarrow and giant goldenrod dried up the most more than 23% moisture content decrease. Variation of moisture content at wild carrot is 15% while wormwood and walnut leaf showed the smallest moisture content decrease only by 6-8 %. The characteristics of drying air and the initial volume of herbs were nearly the same at each measurement. The drying rates of common yarrow and wild carrot were the highest, followed by giant goldenrod, walnut leaf and wormwood.

The drying rate refers to the bulk volume of the material but the volume specific mass transfer surface differs for the different herbs. In the case of common yarrow, giant goldenrod and wild carrot, the plants contained large amounts of inflorescences and leaves which increased the heat and mass transfer surface, so these medicinal plants were able to evaporate on a larger surface, to transfer moisture to the flowing air. During drying, these herbs were placed in the drying chamber with a much larger gap volume than in the case of others because we tried not to compress the material to a great extent, thus preventing the drying air from circulating. The walnut leaf and wormwood contained several leaves and stem parts which means a smaller surface area than the inflorescence, and as well as *thicker* the plant material, making it more difficult to diffuse moisture into the surface. In the case of the walnut leaf, when placed in the drying chamber, the leaves covered each other making it hard for the air to flow through, thus explaining the low drying air velocity.

Table 1. Initial data and measurement results of the medicinal plants to the determination of the drying rate

		Common yarrow	Giant goldenrod	Wormwood	Walnut leaf	Wild carrot
Δt	[min]	397	414	442	378	312
$\bar{T}_{am}$	[°C]	29.3	29.7	28.1	25.2	25.6
$\bar{Y}_{am}$	[gkg^{-1}]	9.2	10.4	11.2	8.7	8.6
$\bar{T}_G$	[°C]	31.2	31.4	30.2	27.7	28.0
v_G	[ms^{-1}]	0.5	0.5	0.5	0.5	0.5
m_0	[kg]	2.917	2.721	1.603	3.481	1.996
H_0	[mm]	240	250	280	280	270
V_0	[m^3]	0.025	0.026	0.029	0.029	0.028
x_0	[%]	71.2	66.0	63.6	62.7	83.3
X_0	[kgkg^{-1}]	2.47	1.945	1.749	1.681	4.996
m_1	[kg]	1.600	1.897	1.273	2.897	0.899
H_1	[mm]	200	230	250	260	130
x_1	[%]	47.6	42.4	57.0	54.4	68.1
X_1	[kgkg^{-1}]	0.91	0.736	1.326	1.192	2.131
Δm_w	[kg]	1.317	0.824	0.330	0.584	1.097
$N_V \pm \delta N_V$	[kgm^{-3}h^{-1}]	7.902 ±0.165	4.549 ±0.091	1.524 ±0.028	3.153 ±0.057	7.441 ±0.138

The moisture ratio could also illustrate the drying characteristics of each plant that gave similar results as drying rate. Figure 6(a) shows the moisture ratio as a function of time in the medicinal plants studied. It can be observed that the greater the gradient of the line is, the more moisture is lost by the sample. Wild carrot, common yarrow and giant goldenrod lost the most moisture during drying compared with the initial state, while walnut leaf and wormwood lost less.

If the temperature of drying air is nearly constant, the only variable parameter is the air velocity that influences the drying rate during the measurements. This is why several measurements were conducted in the case of giant goldenrod at different air velocities to determine the influence of air velocity on the drying rate by the convectional dryer. These examined air velocities were 0.25, 0.1, and natural-convection (in diagrams and tables 0 m/s was used for

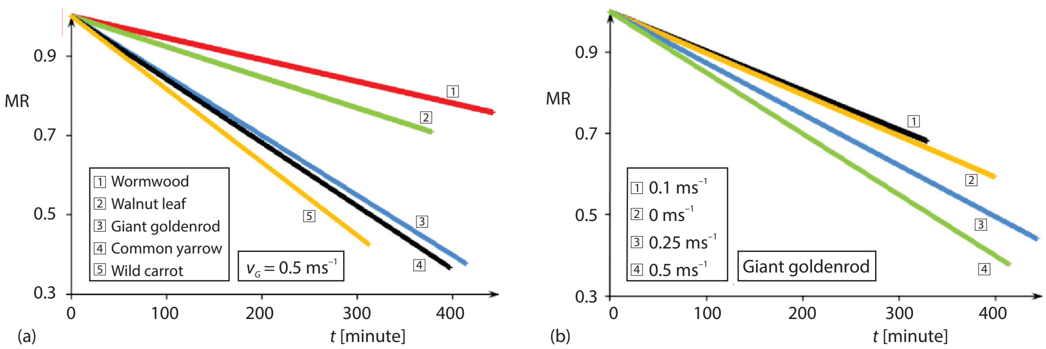


Figure 6. Moisture ratio as a function of time; (a) for the examined medicinal plants at 0.5 m/s air velocity and (b) for giant goldenrod at different air velocities

natural-convection) beyond 0.5 m/s. The reason for the choice of the investigated herb is that it is capable of releasing a significant amount of moisture which allows more accurate and spectacular representation of the changes occurring. Moreover, it was available in large quantities so that it was suitable for testing on this medicinal plant. During measurements the parameters described in section *Determinationof minimum fluidization velocity and volume decrease by fluidized bed dryer* were registered. Table 2 shows initial data and measurement results for giant goldenrod at various air velocities where the measurement error of the drying rate also can be seen.

Table 2. Initial data and measurement results for giant goldenrod drying at various air velocities to the determination of drying rate

v_G	[ms^{-1}]	0.5	0.25	0.1	0
Δt	[min]	414	443	329	399
$\bar{T}_{am}$	[°C]	29.7	26.9	25.8	27.9
$\bar{Y}_{am}$	[gkg^{-1}]	10.4	10.1	10.5	10.5
$\bar{T}_G$	[°C]	31.4	29.9	27.4	27.9
m_0	[kg]	2.721	2.073	1.940	0.820
H_0	[mm]	250	280	270	150
V_0	[m^3]	0.026	0.029	0.028	0.016
x_0	[%]	66	58.6	54	52.9
X_0	[kgkg^{-1}]	1.945	1.416	1.174	1.124
m_1	[kg]	1.897	1.348	1.606	0.749
H_1	[mm]	230	260	260	150
x_1	[%]	42.4	38.4	44.4	40
X_1	[kgkg^{-1}]	0.736	0.625	0.8	0.667
Δm_w	[kg]	0.824	0.725	0.334	0.071
$N_V \pm \delta N_V$	[kgm^{-3}h^{-1}]	4.549±0.091	3.340±0.060	2.149±0.040	0.669±0.025

There is a minimum air velocity which is not worthwhile to go below because it would bring about the same result as if the herbs got dried with ambient air at natural-convection. In addition, there is a maximum air velocity which is not worthwhile to go above because of the pneumatic transport of medicinal plants. There is an optimum velocity at which the highest level of drying can be achieved but further measurements and economic calculations would be necessary to determine such actual air velocity.

The characteristics of drying air and the initial volumes of herbs were nearly the same at each measurement. As expected, the 0.5 m/s air velocity caused the greatest drying rate. The other measurements also corresponded with the expected results that is the lower the velocity of the drying gas was, the lower the drying rate became. Figure 6(b) shows the moisture ratio as a function of time for giant goldenrod at different air velocities. The greatest moisture ratio decrease was at 0.5 m/s and 0.25 m/s air velocities, while the results at 0.1 and 0 m/s air velocities were nearly the same. The 0.1 m/s air velocity was created in the measuring chamber of the convective dryer while at natural-convection the plant was freely dried in the laboratory. In this case, the drying air velocity could even exceed 0.1 m/s, and as shown in fig. 6(b), the moisture ratio became steeper at the natural-convection than at the 0.1 m/s.

Minimum fluidization velocity and volume decrease

If air-flows through a bed of solid particles in an upward direction at a velocity which is greater than the settling velocity of the particles, the solid particles will expand and large instabilities with bubbling and channelling of gas are to be observed. At this state, the solid bed looks like a boiling liquid, the particles blend and bump into each other, therefore, this phenomenon is called as fluidized state. Before the determination of the maximum allowable air velocity, after the medicinal plants spent some days in the laboratory and significantly dried, so they had a low moisture content. Instead of a high moisture content of 60-70%, the herbs had only 10-20% which resulted in lower snatching velocity, so in terms of discharge a more critical state was investigated. When determining the minimum fluidization velocity, the variation of the moisture content of the herbs is negligible because of the short measurement time. During the measurement, air velocity was increased until the plants moved in the chamber, so the fluidized state was reached. From the measurement results the average ambient temperature, the inlet air temperature and the absolute humidity of ambient air were calculated.

The five herbs available were in a similarly dry state and the measurements were conducted in similar circumstances. It was found that the maximum air velocity was 1.8 m/s for common yarrow and walnut leaf, 1.9 m/s for giant goldenrod, and 2.1 m/s for wormwood, and for wild carrot. In this case, the measurement error was also determined which was on average ±0.16 m/s.

Volume decrease was examined as a function of time and moisture content. Measurements were accomplished as described in section *Determinationof minimum fluidization velocity and volume decrease by fluidized bed dryer*. Figure 7(a) shows the results of all measurements in one diagram: volume decrease as a function of time. In the volume of wormwood and common yarrow there was not too much variation during drying. The volume variations of walnut leaf and giant goldenrod were similar. The volume decrease of wild carrot was really intense compared to the other herbs, since only the inflorescence was dried while the rest of the plants had the leaves and stems.

Figure 7(b) shows the volume decrease as a function of moisture content at the herbs studied. The initial moisture content of wild carrot was the highest and the moisture content decrease came to be the greatest, while the volume decrease of the herb was the highest of all during drying. Since the inflorescence had high initial moisture content and drying surface, the moisture content decreased the most in this plant. The moisture content variation of giant goldenrod was also high, but the plant collapsed less during drying, because the stem and leaf parts had better preserved their structure. Walnut leaf and common yarrow showed similar variations during measurements, while wormwood reached the smallest volume decrease and moisture content change.

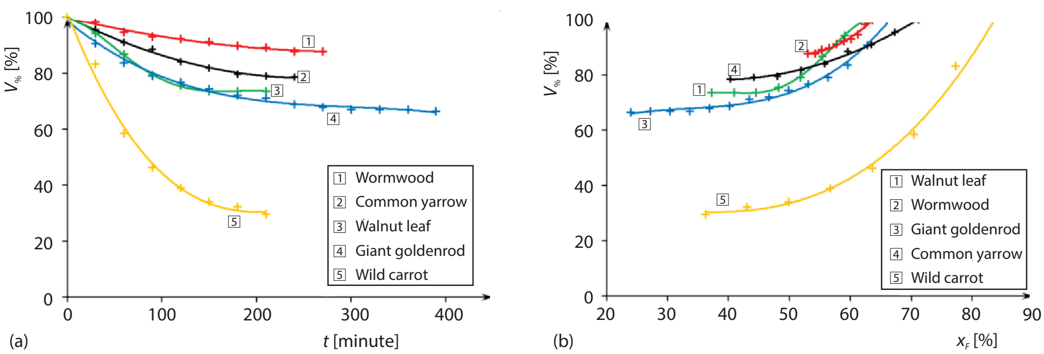


Figure 7. Volume decrease for the studied medicinal plants at 1.5 m/s air velocity; (a) in the function of time and (b) in the function of material moisture content

Average material density and porosity

Measurements for determination of porosity were conducted and measurement results were evaluated according to the specifications described in section *Determination of material density and porosity by air pycnometer*. Table 3 includes the values of bulk density, average material density, average porosity, as calculated for the different herbs and the measurement uncertainty of the average porosity. The largest deviation from the values measured was presented by the large-surfaced walnut leaf, which considerably differs from granular substances in terms of structure. The measured bulk density values can be regarded as realistic; on the other hand, porosity figures show that the herbs fill the space available in an extremely loose arrangement, therefore, they cause relatively low air resistance during drying.

Table 3. Results of the density and porosity for the examined herbs

	X [kgkg^{-1}]	ρ_H [kgm^{-3}]	$\overline{\rho}$ [kgm^{-3}]	$\overline{\varepsilon} \pm \delta\overline{\varepsilon}$
Common yarrow	5.094	101	1445	0.930±0.009
Giant goldenrod	1.462	117	1598	0.927±0.011
Wormwood	3.153	85	966	0.912±0.011
Walnut leaf	2.983	56	2152	0.974±0.007
Wild carrot	8.335	172	1055	0.837±0.018

Conclusions

In our research, the main pre-drying and drying parameters were determined for five different medicinal plants (common yarrow, giant goldenrod, wormwood, walnut leaf, wild carrot) like the drying rate, volume decrease, maximum drying air velocity and porosity.

During drying moisture content decrease was investigated at constant air velocity and from this an average drying rate was determined that is related to the volume of the material. The average drying rate of common yarrow and wild carrot were the highest, followed by giant goldenrod, walnut leaf and wormwood. This variation was dependent on the structure of the plants and the examined parts of the herbs, as common yarrow, wild carrot and giant goldenrod also had denser inflorescence which meant a higher specific surface area than walnut leaf and wormwood. It was also investigated how air velocity influenced moisture content decrease. These measurements involved giant goldenrod. The air velocities were 0.5 m/s, 0.25 m/s, and 0.1 m/s and natural-convection, respectively. As expected, when the air velocity was increased, the drying rate also increased. The required air velocity can be determined by measurements for a particular process where effective drying can be achieved in addition economical operation. During drying the moisture ratio was investigated as a function of time to characterize the efficiency of drying.

The maximum allowable air velocity was determined by a fluidized bed dryer when the medicinal plants were just not yet in a fluidized state and the gas stream did not carry away the material. The five herbs available were in a similarly dry state and the measurements were conducted in similar circumstances. It was found that the maximum air velocity for each medicinal plant was between 1.8 m/s and 2.2 m/s. The volume decrease was determined as a function of time and moisture content. The initial moisture content of wild carrot was the highest and the moisture content decrease came to be the greatest while the volume decrease of the herb was the highest of all during drying. The moisture content variation of giant goldenrod was also high but the plant collapsed less during drying. Walnut leaf and common yarrow showed similar variations during measurements while wormwood reached the smallest volume decrease and moisture content change. In the course of our work, the porosity of five different herbs was measured by an air pycnometer. Knowledge of porosity contributes to the determination of the flow resistance of the bulk of plants and the volume decrease during drying.

During our research, measurement results were presented for the determination of drying parameters of five different herbs which can be used for the operational planning of pre-drying devices.

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Nomenclature

d – diameter, [m]
H – height of product, [m]
MR – moisture ratio
m – mass of product, [kg]
N – drying rate, [kgm^{-3}h^{-1}]
t – time, [s]
T – temperature, [°C]
V – volume, [m^3]
v – air velocity, [ms^{-1}]
X – moisture content of product on a dry basis, [kg_{water}/$kg_{dry\ product}$]
x – moisture content of product on a wet basis, [%]
Y – absolute humidity of gas on dry basis, [kg_{vapor}/$kg_{dry\ gas}$]

Greek symbols

Δ – difference of values
ε – porosity
ρ – density, [kgm^{-3}]

Subscripts and superscripts

* – equilibrium value
% – percentile value
$\bar{}$ – average value
0 – initial value
1 – final value
am – ambient air
ch – chamber
G – gas
H – gaps of product
V – volumetric
w – water

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