Acta Polytechnica **60**(1):49–55, 2020
DOI:10.14311/AP.2020.60.0049

THE EFFECT OF THE FILLING RATIO ON THE OPERATING CHARACTERISTICS OF AN INDIRECT DRUM DRYER

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Abstract. This article investigates the effect of the filling ratio of the indirect rotary dryers on their operating characteristics. For moist biomass drying before combustion, the use of indirect drum dryers heated by a low pressure steam has proven to be highly suitable. Regarding the design of new dryers, it is necessary to experimentally verify the operating characteristics for specific materials and drying conditions. For this purpose, a set of experiments on a steam heated rotary drum dryer were carried out with green wood chips containing 60 to 66 wt% of moisture. The following operational characteristics of the dryer were experimentally determined: drying curves describing the process, square and volumetric evaporation capacities and drying heat consumptions. Based on the experimental results, the effect of various drum filling by dried material on the mentioned operating characteristics was analysed. On the one hand, higher drum filling ratio increases the drying time, on the other hand, the evaporation capacity also increases, while the specific energy consumption does not significantly alter. The maximum value of the evaporation capacity was reached when the drum was filled to 20 wt%. When the filling ratio was increased to 25 wt%, the evaporation capacity experienced almost no change.

Keywords: Indirect drying, biomass, energy consumption, evaporation capacity, drying curve.

1. Introduction

The progress in the use of biomass as a renewable energy source for energy purposes depletes the capacity of its traditional high-quality forms such as wood, straw, etc. Due to the rising price of fuels, low-rank biomass, whose use is often complicated by high water content and which was previously considered as a waste material with a disposal problem, becomes attractive [1]. Nowadays, it is advantageous to use these materials despite poorer operating characteristics or higher demands on the operation of the technology in regards to these factors being eliminated due to the low cost of these materials [1].

Most types of biomass are usually inhomogeneous and vary in quality. Material particles often have a non-uniform granulometry and a high water content affected by the origin and material storage [2]. The water content of residual and waste wood is up to 50 % by weight. Even waste biomass from the food industry (distilleries, breweries, etc.) has a water content ranging from 70 to 95 wt% [1]. Therefore, drying is an essential process for preparing the optimal conditions for a further energetic utilization. Biomass drying improves the fuel heating value and the combustion efficiency, reduces requirements for boiler auxiliary equipment, often reduces emissions and improves boiler operation [3, 4].

Industrial drying is an evaporation of water by transferring heat to the material. There are two main ways of heat transfer to the material: conduction (contact or indirect dryers) or convection (direct dryers) [3, 5]. In indirect dryers, the dried material is separated by a heat transfer surface from the heating medium, it is often steam or hot water. In direct dryers, the dried material and the heating medium are in a direct contact. The drying medium is often hot air, flue gas or steam [6].

The majority of industrial dryers use hot air or flue gas as the drying medium in the direct type configuration [5]. For drying the material in large industrial plants, these variants are commonly used: rotary dryers, fluidized bed dryers and pneumatic dryers [7]. However, these dryers have a relatively low thermal efficiency because the drying medium carried away from the dryer together with the evaporated moisture contains too much waste heat. The most commonly used types of biomass dryers are [3, 5]:

- Convective
  - ▷ Flash
  - ▷ Fluidized bed
  - ▷ Rotary
- Contact
  - ▷ Rotary tube

A practical utilization of convective dryers is traditional and proven, while the use of indirect dryers is not so widespread due to their larger size, higher cost and more complicated design, requiring experimentally verified drying characteristics. However, a major advantage of the indirect drying is the significantly

Dryer type	Typical energy consumption [MJ per kg of evaporated water]
Tunnel dryer	5.5 – 6.0
Band dryer	4.0 – 6.0
Impingement dryer	5.0 – 7.0
Rotary dryer	4.6 – 9.2
Fluid bed dryer	4.0 – 6.0
Flash dryer	4.5 – 9.0
Spray dryer	4.5 – 11.5
Drum dryer (for pastes)	3.2 – 6.5

Table 1. Energy consumption for selected dryers [5].

lower energy intensity, which is fully apparent when large quantities of a material have to be dried.

Drying is an energy consuming process, so the choice of a suitable type of the dryer has to take into account both the dried material's properties and energy demands [1, 3]. The energy efficiency of conventional air dryers varies between 22 and 10 wt%, but the exergy efficiency is less than 16 wt% [8]. For the dryers with an indirect steam heating system, the exergy efficiency is considerably higher than for other dryers using air or steam [9]. The research into innovative methods focuses on increasing the energy efficiency of the process. The approximate values of the energy consumption of commonly used types of industrial dryers based on the current practice are shown in Table 1.

In general, indirect dryers have a better energy efficiency. The typical energy consumption of indirect dryers ranges between 2.8 and 3.6 MJ per kg of evaporated water, while direct dryers consume 4.0 – 6.0 MJ per kg of water evaporated [5].

2. Indirect drying

Indirect (contact) dryers have a wide range of utilization for drying a variety of materials from food and dairy products through energy fuels, such as coal and biofuels, to chemical and other miscellaneous products, such as peat, pigments, carbon black, colloidal clay and many kinds of sludge [5]. The advantage of indirect drying is the increased possibility of recovering the latent heat of waste steam obtained from evaporated water, which is not mixed and polluted by the drying medium as in the case of direct drying [1].

When the dryer is open to the atmosphere at the material input and output zones, there is a small amount of air present in the drying chamber. Drying occurs in an atmosphere corresponding with slightly superheated steam at an ambient pressure [10]. For atmospheric pressure indirect dryer design with minimal ambient air penetration, the waste vapour leaves the process at a temperature close to 100 °C and its condensing temperature decreases only slightly, depending on the air content [11]. The condensing heat of this vapour can be easily returned to the process for a further increase in the total efficiency of the system with an integrated indirect drying or utilized for external consumption [11].

The accurate prediction of heat transfer conditions is of a significant importance for the design and optimization of the operation of these facilities. The theoretical basis of the heat transfer in contact drying process has been investigated by Schlünder and co-workers [12–15]. They introduced the heat transfer from a hot surface to the bed of particulate dried material, which is free flowing or mechanically agitated. For a correct and reliable design of real dryers with a sufficient accuracy, it is necessary to measure and evaluate drying rates and drying times for each specific material to predict and optimize the drying processes in a wider range of operating parameters.

The biomass characteristics, such as water content, bulk density, particle size distribution, influence the operating parameters of the dryer including the energy demand [16]. The final moisture content of the dried material is strongly influenced by the particle diameter and heating medium temperature [17]. A good circulation of biomass particles in the dryers is desired for an intensive and stable drying process [18]. For many kinds of biomass such as highly nonhomogeneous materials with variable particle size rotary drum dryers are most suitable to use [5, 7, 19]. Designing new devices requires experimental determination of the transferable operating characteristics for the specific dried material properties and selected dryer type.

The evaporation capacity is the main operating characteristics used for the dryer design. The evaporation capacity indicates the amount of evaporated water from the dried material relative to the area or volume of the dryer [5]. According to the conditions in the heat transfer process and the type of dryer, the square or volumetric evaporation capacity is used.

For the design of conventional direct rotary dryers, volumetric evaporation capacity is used. For indirect dryers, it is more suitable to use square evaporation capacity. The value of the capacity is influenced by the following operation parameters [10, 11]:

- temperature of the heating medium
- material filling ratio in the dryer

- water content in the material
- dryer revolutions and inclination

The temperature of the heating medium, water content in the material, the dryer revolutions and the inclination are usually given by the design of the dryer or by the operating conditions. This paper focuses on the influence of the dryer filling ratio on other operating characteristics. The dryer filling ratio FR is defined as a ratio of a dried material volume V_{mat} to a dryer volume V_{dryer}

$$FR = \frac{V_{mat}}{V_{dryer}}. \tag{1}$$

For conventional direct rotary dryers, the recommended filling ratio of the dryer by solids is from 10 to 15 % of its volume [5]. For indirect dryers, there is no generally recommended value.

3. Experimental indirect dryer

The experimental indirect dryer (Fig. 1) has a drum configuration with steam as a heating medium. The rotating drum consists of tubes with condensing steam inside. The drying chamber has a diameter of 0.6 m and a length of 2 m. The drum has an adjustable revolution speed. The dryer is heated by saturated steam from a steam network with regulated pressure ranging up to 6 bar. The drying capacity is about 20 kg of evaporated water per hour. The drum is insulated externally with a fibre insulation.

The drum design is shown in Figure 2. Internal fitting and flights increase the total heated surface to twice the drum surface. After a single pass through the dryer, the material is reinserted into the inlet screw feeder and goes through the dryer repeatedly. This procedure simulates a longer drum dimension, thus providing the necessary drying time. It enables the collection of samples of the material for analysis of the actual water content during the drying and adjusting the necessary drying time to achieve the final drying of the material.

4. Results

A set of experiments was carried out on a rotary steam heated dryer with green wood chips. The obtained results were compared with previous experiments of wet bark drying under similar operating conditions as described in [3]. The inlet water content for both tested types of biomass was similar and ranged from 60 to 66 wt%. The following operational characteristics of the dryer were experimentally determined: a drying curve to describe the process, square and volumetric evaporation capacities and drying energy consumption. The tested range of the dryer filling ratio was from 8 to 24 wt%.

The pressure of the heating steam was 3.2 bars (which corresponds with a saturation temperature of 136 °C) for all experiments. The rotation speed of the drum was 2.9 rpm. The overpressure measured within the dryer ranged from 10 to 20 Pa, which is a negligible difference to the atmosphere pressure. After the material got through the dryer, in approximately ten-minute intervals, it was recirculated again into the dryer input. This process substitutes a longer drum dimension and drying time. It also allows material sample collection to determine the actual water content during the drying process.

At the beginning of each measurement, the water content of the material is determined by the laboratory. After each pass through the dryer, a sample is taken to measure the moisture loss of the material over time. From the amount of evaporated water, it is possible to determine the change in the water content of the material and the values of the evaporation capacity. The temperature of the removed material is approximately 80 °C. The heat loss during the fuel transport is included in the overall energy consumption of the dryer, which is determined from the amount of delivered heating steam. This loss is negligible compared to the total energy required for the drying process.

The drying process is usually illustrated by a drying curve defining the dependence of the actual water content in the material on the drying time during the process [1]. Drying curves for measurements with a filling ratio of 12, 16 and 24 wt% are shown in Figure 3. The values are shown at approximate intervals of 10 minutes. Material is recirculated in small portions during periods of several minutes, in order to minimize this period when the material is out of the dryer. The time of one pass through the dryer depends on the revolutions of the drum and the amount of material. The whole material charge passes through the dryer during the period of 20 to 30 minutes.

If the dryer filling ratio is larger, it is necessary to evaporate more water from the material, and therefore a longer drying time is required. Since the drying time varies with different filling ratios, it is preferable to characterize the drying process with a specific evaporation capacity per hour and unit of surface or volume. In order to appropriately compare measurements, the evaporation capacity values are determined for drying to a similar value of final water content around 40 wt% in dried material to illustrate the intensity of drying process in the developed phase. The evaluated values of the evaporation capacities for measurements with various filling ratios are shown in Figure 4 and Figure 5.

The results for wood chips and bark fall very close to the approximation curve, showing very similar drying properties in both materials. The evaporation capacities non-linearly rise with an increasing filling ratio up to the level of 20 wt%. Between the level from 20 to 25 wt%, the square evaporation capacity was between 2.49 and 2.71 $kg \cdot h^{-1} \cdot m^{-2}$ resp. volume evaporation capacity between 26.8 and 29.1 $kg \cdot h^{-1} \cdot m^{-3}$.

Figure 1. Experimental indirect dryer.

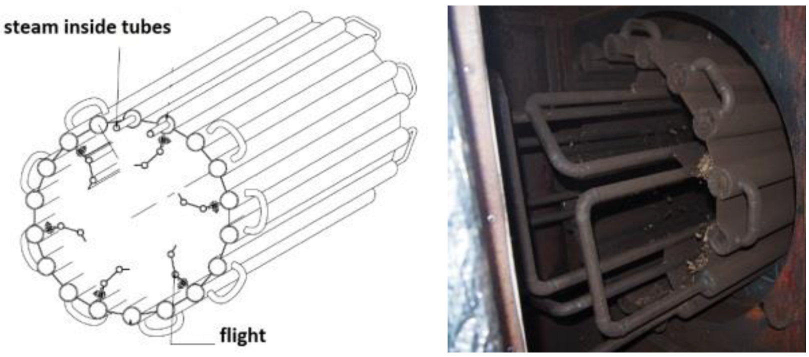

Figure 2. Steam heated rotary drum.

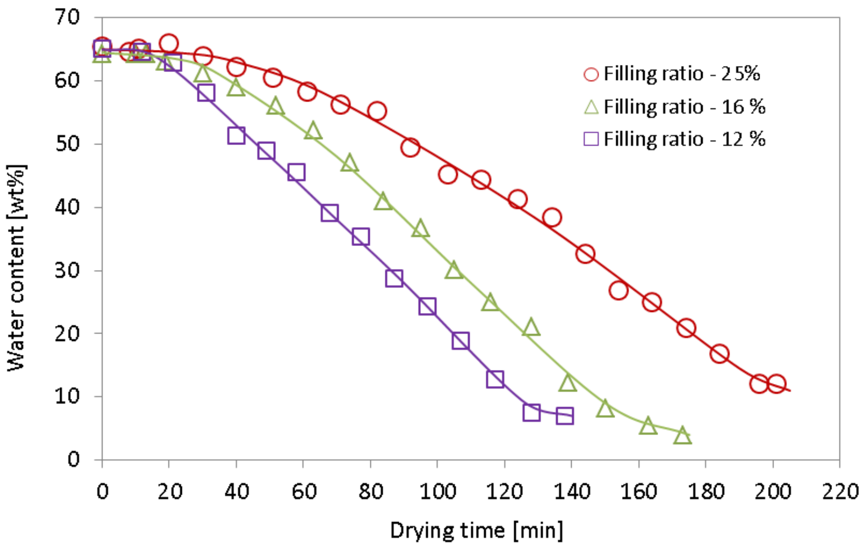

Figure 3. Drying curves for various filling ratio.

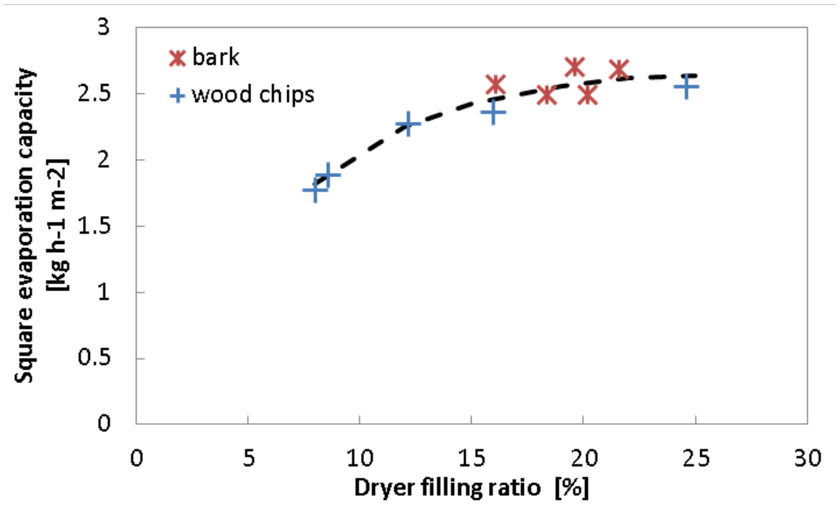

Figure 4. Square evaporation capacity in the dependence on the drum filling ratio.

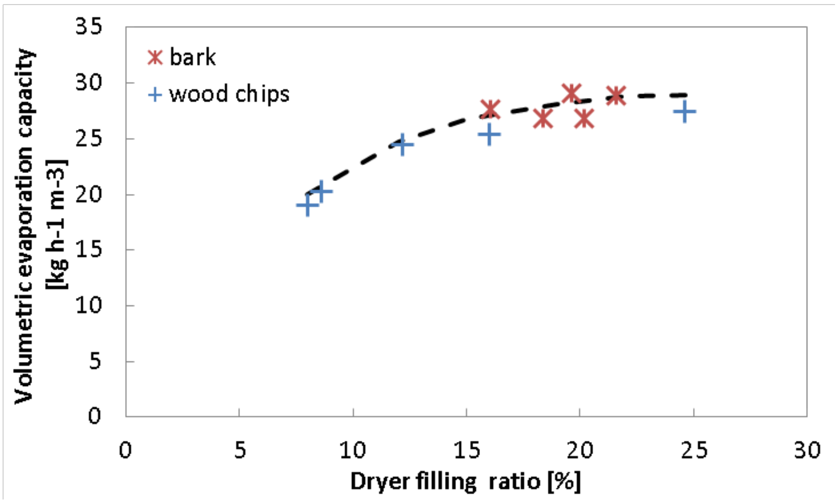

Figure 5. Volumetric evaporation capacity in the dependence on the drum filling ratio.

The energy intensity of the drying is influenced by the heat loss, which depends on the specific solution of the equipment and the thermal insulation. To determine the value of energy consumption without heat loss, a dryer operation without a material charge was measured and balanced. The heat loss was expressed by an increase in the heating steam consumption or condensate production by 3 kg per hour, which was approximately between 10 to 20 wt% of the supplied heat depending on the utilization rate. The energy consumption without heat loss was found to be between 2.67 and 3.34 MJ per 1 kg of evaporated water for biomass in the form of wood chips or bark.

5. Discussion

The initial growth of the evaporation capacity at the higher filling of the drum is related to the increase in the contact area of the material with the heated surface of the dryer. However, this effect is gradually dampened by the deterioration of heat transfer to the growing layer of the material that imposes considerable resistance to the heat conduction. Blending, which should support the heat transfer process to the material, has a limited effect and the evaporation capacity no longer increases from the certain filling ratio of the drum. The maximum value of the evaporation capacity was reached when the drum was filled to 20 wt%. When the filling ratio was increased to 25 wt%, the evaporation capacity experienced almost no change. The maximum values of drying capacities evaluated for specific tested materials, drying conditions and the dryer type are 2.7 $kg\cdot h^{-1}\cdot m^{-2}$ or 29 $kg\cdot h^{-1}\cdot m^{-3}$. It can be expected that the maximum value of the evaporation capacity would be maintained even at a higher filling ratio, but with significantly higher filling ratios, the specific drying rate may begin to decrease.

The energy consumption does not depend on the filling ratio. It mainly depends on the final degree of material drying. The final water content determines the types of water binding in the dried material, as well as the ratio of the heat required for preheating the material to the water evaporation temperature and the heat used to evaporate the water portion from the material (the latent heat of water). To dry the described woody materials with an inlet water content in the range between 60 and 65 wt% to a water content of 40 wt%, the energy consumption would theoretically correspond to about 2.9 MJ per 1 kg of evaporated water. The energy consumption for the tested dryer was experimentally verified as 2.7 to 3.3 MJ per 1 kg of evaporated water for the mentioned types of biomass. In comparison with the commonly used types of dryers [see Table 1], the energy consumption is significantly lower. However, the lower energy consumption is compensated by the larger dimensions of the dryer.

6. Conclusion

An energy efficient use of indirect dryers for drying of green wood chips and wet bark was experimentally verified on a steam heated rotary dryer and the impact of drum filling ratio on the operating characteristics of the dryer was analysed. The drying curve, the surface and volumetric evaporation capacities and the energy consumption were experimentally determined.

Based on the results, the maximum value of the evaporation capacity was reached at a filling ratio of more than 20 wt%. It is evident that the drying time is prolonged with an increasing dryer-filling ratio. Thus, in this interval of the filling ratio, the evaporation capacity does not significantly change and it is suitable to adapt the drying process to other operating conditions, such as the drying time or dryer dimension.

The energy consumption related to 1 kg of evaporated water does not depend on the filling ratio. It mainly depends on the final degree of the material drying. The values of the energy consumption are similar for all dried materials and were experimentally verified in the range from 2.7 to 3.3 MJ per 1 kg of evaporated water, which corresponds with the energy consumption for material preheating and water evaporation. When evaluated, the energy consumption is significantly lower in comparison with conventional types of industrial dryers.

Acknowledgements

This work was supported by Research Centre for Low–Carbon Energy Technologies, CZ. 02.1.01/0.0/0.0/16_019/0000753. We gratefully acknowledge support from this grant.

References

[1] C. J. Ross. *Biomass Drying and Dewatering for Clean Heat & Power*. NorthWest CHP Application Center, Olympia, Washington, USA, 2008.

[2] R. Jirjis. Storage and drying of wood fuel. *Biomass and Bioenergy* **9**(1):181 – 190, 1995. DOI:10.1016/0961-9534(95)00090-9.

[3] W. A. Amos. Report on biomass drying technology. Tech. rep., National Renewable Energy Laboratory, Colorado, USA, 1998. DOI:10.2172/9548.

[4] S. Van Loo, J. Koppejan. *The Handbook of Biomass Combustion and Co-firing*. Earthscan, London, U.K., 2008. DOI:10.4324/9781849773041.

[5] A. S. Mujumdar (ed.). *Handbook of industrial drying*. Marcel Dekker, New York, USA, 1990. DOI:10.1201/9781420017618.

[6] M. Intelvi, A. Picado, J. Martínez. Contact drying simulation of particulate materials: A comprehensive approach. *Engineering and Technology* **59**:1669–1676, 2011. DOI:10.13140/RG.2.1.2632.6008.

[7] N. Nikolopoulos, I. Violidakis, E. Karampinis, et al. Report on comparison among current industrial scale lignite drying technologies (A critical review of current technologies. *Fuel* **155**:86 – 114, 2015. DOI:10.1016/j.fuel.2015.03.065.

[8] E. Terehovics, I. Veidenbergs, D. Blumberga. Energy and exergy balance methodology. Wood chip dryer. *Energy Procedia* **128**:551 – 557, 2017. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2017, 10-12 May 2017, Riga, Latvia, DOI:10.1016/j.egypro.2017.09.008.

[9] A. Alamia, H. Ström, H. Thunman. Design of an integrated dryer and conveyor belt for woody biofuels. *Biomass and Bioenergy* **77**:92 – 109, 2015. DOI:10.1016/j.biombioe.2015.03.022.

[10] E. R. Canales, R. M. Bórquez, D. L. Melo. Steady state modelling and simulation of an indirect rotary dryer. *Food Control* **12**(2):77 – 83, 2001. DOI:10.1016/S0956-7135(00)00027-X.

[11] J. Havlík, T. Dlouhý. Integration of biomass indirect dryers into energy systems. *Journal of Chemical Engineering of Japan* **50**(10):792 – 798, 2017. DOI:10.1252/jcej.16we322.

[12] E. U. Schlünder. Heat transfer to packed and stirred beds from the surface of immersed bodies. *Chemical Engineering and Processing: Process Intensification* **18**(1):31 – 53, 1984. DOI:10.1016/0255-2701(84)85007-2.

[13] E. U. Schlünder, N. Mollekopf. Vacuum contact drying of free flowing mechanically agitated particulate material. *Chemical Engineering and Processing: Process Intensification* **18**(2):93 – 111, 1984. DOI:10.1016/0255-2701(84)85012-6.

[14] E. Tsotsas, E. U. Schlünder. Contact drying of mechanically agitated particulate material in the presence of inert gas. *Chemical Engineering and Processing: Process Intensification* **20**(5):277 – 285, 1986. DOI:10.1016/0255-2701(86)80021-6.

[15] E. Tsotsas, E. U. Schlünder. Vacuum contact drying of mechanically agitated beds: The influence of hygroscopic behaviour on the drying rate curve. *Chemical Engineering and Processing: Process Intensification* **21**(4):199 – 208, 1987. DOI:10.1016/0255-2701(87)80017-X.

[16] A. Del Giudice, et al. Wood chip drying through the using of a mobile rotary dryer. *Energies* **12**(9):1590, 2019. DOI:10.3390/en12091590.

[17] P. L. Simona, P. Spiru, I. V. Ion. Mathematical modelling of sawdust drying process for biomass pelleting. *Energy Procedia* **141**:150 – 154, 2017. Power and Energy Systems Engineering, DOI:10.1016/j.egypro.2017.11.028.

[18] Y. Liu, J. Peng, Y. Kansha, et al. Novel fluidized bed dryer for biomass drying. *Fuel Processing Technology* **122**:170 – 175, 2014. DOI:10.1016/j.fuproc.2014.01.036.

[19] C. Gu, X. Zhang, B. Li, Z. Yuan. Study on heat and mass transfer of flexible filamentous particles in a rotary dryer. *Powder Technology* **267**:234 – 239, 2014. DOI:10.1016/j.powtec.2014.06.059.