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INVESTIGATION OF THE EFFICIENCY OF A BEET PULP FILTRATION DRYING PROCESS

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Abstract. This article presents the results of experimental studies investigating the energy consumption per 1 kg H_2O required for the filtration drying of beet pulp. The optimal process parameters for the removal of 1 kg of moisture from the dried beet pulp were determined, which included the height of the layer of dried material H=120 mm, the thermal agent temperature T = 90 °C and the thermal agent velocity v_0 = 1.76 m/s. Regarding these parameters, the total energy consumption for drying by the filtration method from the initial moisture content of 88.12 % wt. to the final moisture level of 14 % wt. is 3,515 kW·h/kg H_2O. Based on the experimental data, a calculation was made for an industrial filtration drying unit, for which the cost of removing 1 kg of moisture from beet pulp was determined: 3,28 kW·h/kg H_2O. To evaluate the efficiency of the filtration drying process, we conducted a comparative analysis of the drying of beet pulp at a comparable capacity in a drum dryer. According to the calculations, the energy costs for removing 1 kg of moisture from beet pulp in a drum dryer are 3.11 kW·h/kg H_2O. Considering the estimation of calculations and a significant reduction in the drying time with the filtration method (~10 times), it is possible to conclude that filtration drying is a beneficial and efficacious technique for beet pulp drying.

Keywords: filtration drying, beet pulp, biomass, calculation, waste management, recycling.

1. Introduction

In recent decades, humanity has faced an increasingly pressing issue of substantial industrial waste accumulation, accelerating with population growth and rising production volumes (Muir, Anderson, 2022). The accumulation of waste leads to environmental pollution issues, which affect human lives. The problem of environmental management and waste recycling is one of the most critical challenges facing humanity in the 21st century.

In Ukraine, a substantial challenge lies in recycling secondary raw materials and diversifying waste from the agricultural and food production sectors (Novikova et al., 2022). A significant number of crops are planted and processed in our country (Cheremisina, 2021). Food industry enterprises generate a substantial amount of industrial waste of plant origin – beer pellets, post-alcohol bard, coffee production, fruit pomace, and others that can be reused in various economic sectors (Ivashchuk et al., 2024, a).

Excess moisture is the common factor that unites waste from the food production industry. That is an obstacle to its reuse; moisture is often above 65 % wt. It rapidly degrades recycled materials and reduces the shelf life to 2–3 days (Ivashchuk et al., 2024, a). As a result of rapid deterioration, vegetable waste can cause pollution of the environment, soil, air, groundwater, etc. (Tuchkova et al., 2022).

The drying of recycled materials to remove excess moisture is often an energy-intensive process,

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which can limit the economic viability of the resulting product. At present, drum-type dryers are the most commonly used for the drying of biomass (Mujumdar, 2014; Thibault et al., 2010), which is an energy-intensive process due to the technological and design features of such dryers. This research aimed to evaluate the efficiency of beet pulp filtration drying, a sugar production industry waste product (Misra, Shrivastava, 2022; Dygas et al., 2023). Dried beet pulp can be successfully applied as a feed in animal husbandry (Semenova et al., 2013; Joanna et al., 2018). The efficiency of the filtration drying process is contingent upon the time required for the drying of the material, as well as the quantity of the thermal agent necessary for the process. Additionally, the energy consumed in overcoming the feedstock layer with the thermal agent must be considered. Most energy consumed in biomass drying is spent on these significant cost items.

The article represents a continuation of the work previously described in (Ivashchuk et al., 2024, b), which outlined the kinetic laws of filtration drying of beet pulp. This earlier work generalized the dependencies of changes in the initial wet material's moisture content and the process's duration. The study of the hydrodynamics of the movement of a thermal agent through a stationary layer of beet pulp (Ivashchuk et al., 2024, c) allows for the determination of the pressure drop that occurs during the process.

2. Experimental part

The object of the study was beet pulp obtained from the production line of a local sugar factory in the Lviv region of Ukraine (Ivashchuk et al., 2024, c). Experimental studies of the filtration drying of sugar production waste, specifically beet pulp, were conducted on an experimental installation. The scheme and principle of this setup are described in detail in reference (Ivashchuk et al., 2024, d). The methodology employed in experimental studies and related measurements is outlined in (Ivashchuk et al., 2024, d; Ivashchuk et al., 2024, e).

The kinetic laws of filtration drying of beet pulp and the laws of the hydrodynamics of the movement of the thermal agent through a stationary layer of the dried material were investigated using this installation.

The results of the generalized research data indicate that the mathematical dependences of the duration of filtration drying of beet pulp production waste in the drying period of complete saturation of the thermal agent with moisture τ_I and the period of partial saturation of the thermal agent with moisture τ_{II} are as follows (Ivashchuk et al., 2024, b):

$$\tau_I = \frac{1 - \frac{w^c}{w_0^c}}{6.159 \cdot 10^{-5} \cdot T^{0.61} \cdot v_0^{1.547} \cdot e^{-12.753 \cdot H}} \; ; \qquad (1)$$

$$\tau_{II} = \frac{0.303 \cdot (w_0^c - w_{cr}^c) - ln(\frac{w^c - w_e^c}{w_{cr}^c - w_e^c})}{0.303 \cdot N} , \qquad (2)$$

where H is the material layer height, m; w^c, w^c_0, w^c_e, w^c_{cr} are the running, initial, equilibrium moisture content of the material and critical moisture content of the material at the end of the period of complete saturation of the thermal agent with moisture, respectively, kg H_2O/kg dry material; τ is the drying time, s; τ_{cr} is the critical time to reach the moisture content value w_{cr}, s; T is the thermal agent temperature, °C; N is the drying rate during the period of complete saturation of the thermal agent with moisture, kg H_2O/(kg dry material · s).

The resistance of the stationary layer of dried beet pulp ΔP is described by the equation for the indicators of technologically feasible industrial layer heights H = 80–120 mm (Ivashchuk et al., 2024, c):

$$\Delta P = 9602 \cdot H \cdot v_0 + 13474 \cdot H \cdot v_0^2 \, . \qquad (3)$$

The technologically feasible parameters of filtration drying of beet pulp in the experimental installation were determined according to the methodology described in detail in (Ivashchuk et al., 2024, e). In general, the energy consumption for the evaporation of 1 kg of moisture during filtration drying was calculated as the sum of the energy consumption for heating the thermal agent to remove 1 kg of moisture from the material layer $^{Qlab}{}_{t.a.}$ and overcoming the pressure drop to remove 1 kg of moisture during drying $^{Qlab}{}_{\Delta P}$ (Ivashchuk et al., 2024, e):

$$Q^{lab} = Q^{lab}_{t.a.} + Q^{lab}_{\Delta P} \, . \qquad (4)$$

To evaluate the efficiency of the industrial use of a filtration drying machine for purposes of beet pulp drying, we calculated the parameters of the industrial process based on the selected technologically feasible process parameters according to the methodology described step by step in (Ivashchuk et al., 2024, e). During the calculations, the parameters of the thermal agent were determined using the I-d diagram of the state of moisture air (Dziubenko et al., 2018). The total amount of energy required for the industrial process of filtration drying N was calculated as the sum of the energy needed to heat the necessary quantity of thermal agent $N_{t.a.}$ and the power required to ensure the requisite speed of transfer of the thermal agent through the layer of dried material (Ivashchuk et al., 2024, e):

$$N = N_{t.a.} + N_{fan}. \quad (5)$$

The heat capacity of beet pulp c_{mat} was determined according to equation (Ivashchenko et al., 2014):

$$c_{mat} = 1.276 + 1.93 \cdot \omega + 0.0115 \cdot t - 0.0035 \cdot \omega \cdot t, \quad (6)$$

where ω is a material moisture content.

A calculation was conducted for a drum dryer to evaluate the efficiency of the filtration method of drying beet pulp in an industrial context, given that this type of equipment is commonly employed for biomass drying (Rezaei et al., 2022; Sai, 2013).

3. Results and Discussion

The results of the calculation of the optimal parameters for the filtration drying of beet pulp from an initial moisture content of 88.12 % wt. to a final moisture content of 14 % wt., by the data obtained from the experimental installation (Ivashchuk et al., 2024, d), are presented in Table 1.

The analysis of energy consumption for the removal of 1 kg of moisture from beet pulp demonstrates the following dependencies on the parameters of the filtration and drying method: the specific N^{lab} values decrease with a reduction in the height of the material layer, an increase in the temperature of the thermal agent, and a decrease in the speed of the thermal agent (Table 1). The results of the calculations indicate that the most efficient energy consumption for the removal of 1 kg of moisture from the material layer during the filtration drying of beet pulp is achieved with the following experimental parameters (No. 7) (H = 120 mm, T= 90 °C, v_0 = = 1.76 m/s), constituting 12654.758 kJ/kg H_2O або 3.515 kW·h/kg H_2O (Table 1).

To determine the energy usage costs for a filtration drying process in an industrial device, we calculated the costs according to the methodology outlined in the reference (Ivashchuk et al., 2024, e). The initial data used in the calculation are provided below in Table 2.

Table 1

The energy consumption per kilogram for the filtration drying of beet pulp

No.	H, m	T, °C	v_0, m/s	ΔP, Pa	τ, s	$Q^{lab}_{t.a.}$, kJ/ kg H_2O	$Q^{lab}_{\Delta P}$, kJ/ kg H_2O	Q^{lab}, kJ/ kg H_2O	N^{lab}, kW·h/ kg H_2O
1	0.04	70	1.76	2138	1280	13882.080	685.482	14567.562	4.047
2	0.08			4277	2211	11989.797	1184.086	13173.884	3.659
3	0.12			6415	3428	12393.435	1835.923	14229.359	3.953
4	0.16			8553	5263	14268.394	2818.231	17086.625	4.746
5	0.12	60		6415	4328	12892.088	2317.424	15209.512	4.225
6		80		6415	2796	11787.429	1497.325	13284.754	3.690
7		90		6415	2380	11380.004	1274.754	12654.758	3.515
8		70	1.24	3777	5052	12867.207	1122.170	13989.378	3.886

Table 2

Input parameters for calculation of filtration drying of beet pulp

Parameter	Value
Productivity by source material G_1, kg·h	1000
Initial material moisture content ω_1, %	88
Final material moisture content ω_2, %	14
Bulk density of the material ρ_b, kg / m^3	432.36
Ambient temperature T_0, °C	20
Initial humidity of thermal agent ϕ_0, %	60
Initial thermal agent temperature T_1, °C	90
Final thermal agent temperature T_2, °C	60
Initial material temperature t_1, °C	20
Final material temperature t_2, °C	52
Thermal agent velocity v_0, m/s	1.76
Height of material layer H, m	0.12

The results of the energy consumption calculation for the industrial filtration drying process are presented below (Table 3).

Based on the experimental data and verification calculations, the absolute deviation in the calculated mass flow rate of the thermal agent $G_{t.a.}$ is 1.91 % and 2.48 %, respectively. These values are based on the data of the material $G'_{t.a.}$ and the heat balance $G''_{t.a.}$ Thus, the results obtained can be considered correct.

To evaluate the efficiency of the proposed drying method, the effectiveness of drying beet pulp in a drum dryer for a comparable level of productivity in terms of wet material G_1 was determined. The temperature of the thermal agent t_1 = 140 °C was chosen for drying in a drum dryer. The recommended temperature for drying biomass was considered (Jewiarz, 2020); the initial data for the calculation are presented in Table 4 below.

The results of the energy consumption calculation for the industrial filtration drying process are presented below (Table 5).

By the material balance, the deviation margin is 0.41 % (Table 5), which allows us to conclude that the results are accurate.

The data analysis obtained for drying beet pulp by the filtration method and in a drum dryer demonstrates that, despite the slightly higher energy consumption associated with filtration drying, there is a notable reduction in the drying time, approximately 10 times. This evidence supports the conclusion that the filtration drying method is more efficient. In light of the fact that the calculation is an estimate and does not include energy costs for auxiliary equipment of the drum dryer (such as the cyclone for cleaning the exhaust gases and the drum drive, among others), the prospects for utilizing filtration drying for beet pulp appear to be promising.

Table 3

The results of the calculation of the filtration drying process of beet pulp

Parameter	Value
Productivity by source material G_1, kg·h	1000
Initial material moisture content w/w w^c_0, kg H_2O / kg dry mat.	7.33
Final material moisture content w^c, kg H_2O / kg dry mat.	0.16
Total drying time τ, h	0.65
Belt conveyor width B, m	1.4
Belt conveyor length L, m	9
Volume of material on conveyor V_{mat}, m^3	1.512
Mass of wet material on the conveyor G_{mat}, kg	653.73
Conveyor belt speed v_{tr}, m/s	0.0038
Improved performance in wet material G'_1, kg·h	1000.66
Volumetric flow rate of the thermal agent $Q_{t.a.}$, m^3/h	79833.60
Mass flow rate of the heat transfer fluid $G_{t.a.}$, kg·h	77678.09
Dry material mass G_d, kg·h	120.08
Mass of material at the outlet G_2, kg·h	139.63
Amount of moisture W, kg·h	861.04
Initial moisture content of thermal agent d_1, kg H_2O/ kg dry mat.	0.0087
Final moisture content of thermal agent d_2, kg H_2O/ kg dry mat.	0.02
Mass flow rate of thermal agent $G'_{t.a.}$, kg·h	76197.88
Heat amount needed for moisture evaporation from material Q_{ev} kJ·h	1980383.02
Heat amount for steam formation Q_v, kJ·h	43706.19
Heat amount for moisture heating in material Q_{H20}, kJ·h	46900.64
Heat amount for heating wet material Q_{mat}, kJ·h	13027.78
Heat amount to heat the residual moisture in the material Q_{res}, kJ·h	2620.98
Total heat consumption Q, kJ·h	2295302.46
Thermal agent mass flow G''t.a., kg·h	75752.56
Energy amount for heating the required amount of thermal agent $N_{t.a}$, kW·h	2542.52
Energy consumption for removing 1 kg of moisture in terms of the required amount of thermal agent $l_{t.a.}$, kW·h/kg H_2O	2.95
Energy amount required to operate the fan N_{fan}, kW·h	284.52
Total energy required for the filtration drying process N, kW·h	2827.04
Total energy consumption to remove 1 kg of moisture for the filtration drying process l, kW·h/kg H_2O	3.28

Table 4

Input parameters for calculating the process of beet pulp drying in a drum dryer

Parameter	Value
Productivity by source material G_1, kg·h	1000
Initial material moisture content ω_1, %	88
Final material moisture content ω_2, %	14
Bulk density of the material ρ_b, kg/m^3	432.36
Ambient temperature T_0, °C	20
Initial humidity of thermal agent ϕ_0, %	60
Initial thermal agent temperature T_1, °C	140
Final thermal agent temperature T_2, °C	90
Initial material temperature t_1, °C	20
Final material temperature t_2, °C	87
Thermal agent velocity v_0, m/s	3
Drum filling ratio with wet material β	0.2
Drum tension by moisture content A_V, kg/ m^3·h	15

Table 5

Calculation results of the process of beet pulp drying in a drum dryer

Parameter	Value
Productivity by source material G_1, kg·h	1000
Initial material moisture content w/w w^c_0, kg H_2O / kg dry mat.	7.33
Final material moisture content w^c, kg H_2O / kg dry mat.	0.16
Total drying time $\tau^{r.d}$, h	6.77
Dry material mass G_d, kg·h	120
Mass of material at the outlet G_2, kg·h	139.53
Amount of moisture W, kg·h	860.47
Drying drum volume $V^{r.d.}$, m^3	57.36
Drum length $L^{r.d.}$, m	12
Drum diameter $D^{r.d.}$, m	2,8
Actual drying space volume $V^{r.d.}{}_2$, m^3	74
Mass of material in dryer $G^{r.d.}$, kg	6398.93
Initial moisture content of thermal agent d_1, kg H_2O/ kg dry mat.	0.0087
Final moisture content of thermal agent d_2, kg H_2O/ kg dry mat.	0.027
Mass flow rate of the thermal agent $G^{r.d.}{}_{t.a.}$, kg·h	47019.96
Heat amount needed for moisture evaporation from material Q_{ev} kJ·h	1979069.77
Heat amount for steam formation Q_v, kJ·h	82174.42
Heat amount for moisture heating in material Q_{H20}, kJ·h	72106.98
Heat amount for heating wet material Q_{mat}, kJ·h	29510.02
Heat amount to heat the residual moisture in the material Q_{res}, kJ·h	4716.26
Total heat consumption Q, kJ·h	2384335.19
Thermal agent mass flow G''t.a., kg·h	47214.56
Energy amount for heating the required amount of thermal agent $N_{t.a}$, kW·h	2649.26
Energy consumption for removing 1 kg of moisture in terms of the required amount of thermal agent $l_{t.a.}$, kW·h/kg H_2O	3.08
Energy amount required to operate the fan N_{fan}, kW·h	24.18
Total energy required for the filtration drying process N, kW·h	2673.45
Total energy consumption to remove 1 kg of moisture for the filtration drying process l, kW·h/kg H_2O	3.11

Table 6

Results comparison of calculation of the process of beet pulp drying by filtration and in a drum dryer

Parameter	Filtration Drying Unit	Drum Drying Unit
Productivity by source material G_1, kg·h	1000.66	1000
Total drying time τ, h	0.65	6.77
Total energy required for the drying process N, kW·h	2827.04	2673.45
Total energy consumption to remove 1 kg of moisture for the filtration drying process l, kW·h/kg H_2O	3.28	3.11

Furthermore, additional advantages of the filtering method include reduced unit size and the ability to use secondary heat to warm the thermal agent.

4. Conclusions

To sum up, the technologically rational parameters of the process of filtration drying of beet pulp were determined in this article. Parameters were based on the data obtained in the experimental installation. Based on the determined technologically rational parameters of filtration drying, the energy consumption for removing 1 kg of moisture from the material was calculated, which for beet pulp is 3.28 kWh/kg H_2O.

To compare the effectiveness of the filtration drying method, we calculated the drying of beet pulp with similar productivity in a drum unit. According to the calculations, the energy consumption for removing 1 kg of moisture from beet pulp in a drum installation is 3.11 kWh/kg H_2O.

It can be concluded that filtration drying is advantageous and efficient for beet pulp drying, considering the estimation of calculations and a significant reduction in drying time when using the filtration method.

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