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HYDRODYNAMICS OF FILTRATION DRYING OF WILD CARROT POMACE

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Abstract. The paper presents the results of a study on the hydrodynamics of the stationary layer of wild carrot pomace during filtration drying, as a raw material for the production of ecological alternative solid fuel. The main geometric parameters of individual wild carrot pomace particles and the physicomechanical properties of the stationary layer were determined experimentally. A diagram of the experimental setup is provided. The results of the experimental studies are presented in the form of functional dependencies of pressure loss $\Delta P = f(v_0)$ and Euler's criterion as a function of Reynolds number and the geometric simplex $Eu = f(Re, G)$. The feasibility of pretreatment of wild carrot pomace for alternative biofuel production is justified. The obtained results allow for predicting energy consumption when developing equipment for the filtration drying of this material.

Keywords: wild carrot pomace, stationary layer, hydrodynamics, filtration drying, sustainable development.

1. Introduction

Wild carrot (Daucus carota) contains a significant number of phenolic compounds, terpenes, and flavonoids (Ismail et al., 2024). This plant also has antipyretic, anti-inflammatory, anticancer, and antibacterial properties (Boadi et al., 2021). For this reason, wild carrot extract is widely used in the pharmaceutical industry (Stanojević et al., 2023).

However, as a result of extracting useful substances from wild carrot, a large amount of waste is produced – wild carrot pomace. Currently, plant waste in the pharmaceutical industry is used inefficiently and, in many cases, is disposed of by being sent to landfills. As plant waste continues to accumulate, it occupies significant areas of landfill sites. Decomposition of this waste occurs in landfills, contaminating groundwater. Chemical leachate is released during the decomposition process, penetrating the soil and leading to toxic contamination. Therefore, there is a problem of ecological disposal of this waste.

One way to dispose of wild carrot pomace is to recycle it as secondary raw material. This will reduce the negative impact of harmful substances on the soil and decrease greenhouse gas emissions (Kumar Sarangi et al., 2023). Processing wild carrot pomace waste also has economic significance, as it contributes to the development of new technologies in the field of pharmaceutical waste disposal (Ivashchuk et al., 2024, a). In Ukraine, the system for managing plant waste is unsatisfactory, so processing and reusing wild carrot pomace contributes to the development of a sustainable system.

Wild carrot pomace, as an organic raw material of plant origin, can be used for the production of biofuel – an alternative, environmentally friendly source of energy (Srivastava et al., 2021). The process of recycling wild carrot pomace is complicated by its high moisture content (approximately 60 % by mass). This directly affects the storage time of this

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raw material for biofuel production. Therefore, one of the key stages in processing plant waste, particularly wild carrot pomace, is drying (Zhou et al., 2019). For the production of fuel briquettes, the moisture content of the plant material must be between 7 and 14 % by mass (Guibunda et al., 2024).

After analyzing the literature (Atamanyuk et al., 2018), it was determined that the most efficient method for drying solid dispersed materials is filtration drying. Filtration drying (Ivashchuk et al., 2024, b) is carried out by filtering the gas flow through a stationary layer of porous material under the influence of pressure difference. The key indicator of the efficiency of this method is the level of specific energy consumption required to maintain the pressure difference (Kobeyeva et al., 2022). The analysis of the hydrodynamics of filtration drying allows for predicting these energy costs and optimizing the drying process (Ivashchuk et al., 2022).

2. Experimental part

The object of the study was wild carrot pomace obtained from a local pharmaceutical production facility. The hydrodynamics of the stationary layer of wild carrot pomace were studied using an experimental setup described in (Atamanyuk et al., 2020). The methodologies used to determine the main physicomechanical characteristics of particles and investigate the hydrodynamics of gas flow filtration through the stationary layer of wild carrot pomace are provided in (Atamaniuk, Humnytskyi, 2013).

The hydrodynamic characteristics of the stationary layer directly affect the efficiency of filtration drying. The filtration speed of the gas flow through the layer of wild carrot pomace determines the intensity and economic feasibility of filtration drying for this material.

The hydrodynamics of the stationary layer of wild carrot pomace were studied at various material heights in the container, specifically: 30 mm, 60 mm, 90 mm, 120 mm, and 150 mm. The initial bulk density for all the studied heights was the same. Each experiment was conducted at least 7 times with new portions of wild carrot pomace.

The pressure losses in the stationary layer of wild carrot pomace were determined using the Darcy – Weisbach equation:

$$\Delta \mathrm{P} = \lambda \cdot \frac{\mathrm{H_e}}{d_e} \cdot \frac{\rho \cdot \upsilon^2}{2}, \qquad (1)$$

where λ is the resistance coefficient of the layer; H_e is the equivalent length of the channels through which the gas flow moves, defined as $H_e = 1.5 \cdot H$, m; d_e is the equivalent diameter of the wild carrot pomace particles, m; ρ is the density of the gas flow, kg/m³; υ is the actual velocity of the gas flow through the stationary layer of wild carrot pomace, m/s.

Considering that the hydraulic resistance coefficient λ depends on the Reynolds number, equation (1) is presented in the form of a two-term expression that takes into account both the losses due to friction and the losses associated with local resistances:

$$\Delta \mathrm{P} = \mathrm{A} \cdot \frac{\mu \cdot \mathrm{a}^2}{32 \cdot \varepsilon^3} \cdot \mathrm{H_e} \cdot \upsilon_0 + \mathrm{B} \cdot \frac{\rho \cdot \mathrm{a}}{8 \cdot \varepsilon^3} \cdot \mathrm{H_e} \cdot \upsilon_0^2, \qquad (2)$$

where A and B are unknown coefficients, the values of which were determined through experimental studies; μ is the dynamic viscosity of the gas flow, Pa·s; a is the effective specific surface area of all particles in the stationary layer of wild carrot pomace, m²/m³; ε is the porosity of the stationary layer of wild carrot pomace, m³/m³; υ_0 is the fictitious filtration velocity of the gas flow through the stationary layer of material, m/s.

To determine the unknown coefficients “*A*” and “*B*” in equation (2), linearization was performed with respect to the fictitious filtration velocity of the gas flow, after which it was presented in the following form:

$$\frac{\Delta \mathrm{P}}{\mathrm{H} \cdot \upsilon_0} = \mathrm{A}^* + \mathrm{B}^* \cdot \upsilon_0, \qquad (3)$$

where $\mathrm{A}^* = \mathrm{A} \cdot \frac{\mu \cdot \mathrm{a}^2}{32 \cdot \varepsilon^3}$ and $\mathrm{B}^* = \mathrm{B} \cdot \frac{\rho \cdot \mathrm{a}}{8 \cdot \varepsilon^3}$.

The first part of this equation remains a constant for the given experimental conditions, while in the second part, the variable parameter is solely the fictitious velocity.

By empirically determining the unknown coefficients of equation (3) for a specific dispersed material and the defined experimental conditions, it can be used for practical calculations of drying equipment. This allows for the prediction of pressure losses during filtration drying, but only within the range of investigated gas flow velocities.

In practice, it is more convenient to use the dimensionless form of the calculation dependencies, as they account for the specifics of the gas flow movement and the influence of the geometric characteristics of the drying equipment on pressure losses in the stationary layer of the dispersed material. In this approach, pressure losses are described by a functional dependence of the Euler criterion on the Reynolds criterion and the geometric simplex.

Filtering the gas flow through a stationary layer of wild carrot pomace represents a mixed hydrodynamics goal. Since the gas flow during filtration through the stationary layer of wild carrot pomace washes each particle individually (external goal) and moves through the channels between the particles (internal goal). There is no theory for the mixed hydrodynamics goal, so the external and internal goals were studied separately.

The value of Euler's number for the external goal of hydrodynamics was determined based on the dependency:

$$Eu = A \cdot Re^x \cdot \left(\frac{H}{d_p}\right)^y, \quad (4)$$

where Eu – Euler criterion $Eu = \Delta P/(\rho \cdot v^2)$; Re – Reynolds criterion $Re = v \cdot d_p \cdot \rho/\mu$; H – height of the stationary layer of wild carrot pomace, m; d_p – average diameter of particles of wild carrot pomace, m.

For the study of the internal problem of hydrodynamics, the following equation was used:

$$Eu = A \cdot Re_e^x \cdot \left(\frac{H_e}{d_e}\right)^y, \quad (5)$$

where Re is the equivalent value of the Reynolds criterion $Re_e^x = v \cdot d_e \cdot \rho/\mu$.

3. Results and Discussion

The results of the granulometric composition of wild carrot pomace are presented in Table 1 and Fig. 1.

Table 1

The granulometric composition of wild carrot pomace

Fraction $d \cdot 10^3$, m	0.1–0.14	0.14–0.315	0.315–0.63	0.63–1.25	1.25–2.5	2.5–5	Total
Weight of the fraction G, kg	0.00024	0.01013	0.315-0.63	0.1506	0.02674	0.00101	0.2
Percentage content, % mass	0.12	5.06	5.64	75.30	13.37	0.51	100

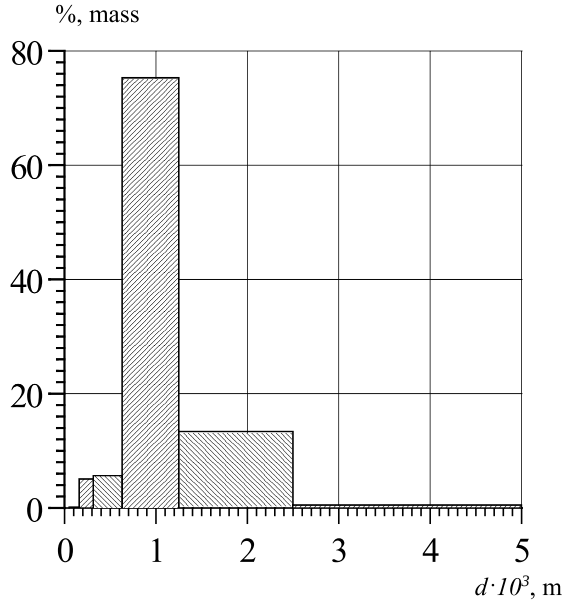

Fig. 1. Granulometric composition of the stationary layer of wild carrot pomace

The geometric particle sizes of wild carrot pomace were determined using an MBB-1A electron microscope (Fig. 2). More than 100 samples of ground wild carrot pomace particles were analyzed.

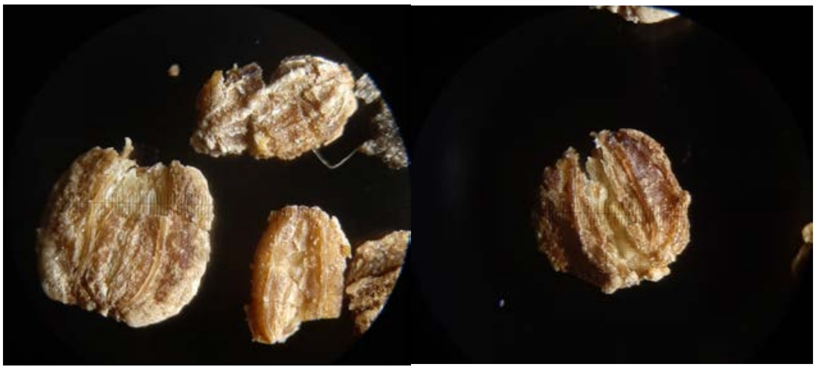

Fig. 2. Measurement of the geometric size of wild carrot pomace particles using an MBB-1A microscope

The averaged geometric particle sizes are provided in Table 2.

Table 2

Geometric characteristics of wild carrot pomace

Fraction $d \cdot 10^3$, m	Average linear dimensions, m			Average particle diameter $d_p \cdot 10^3$, m
	Length, $a \cdot 10^3$, m	Width, $b \cdot 10^3$, m	Thickness, $c \cdot 10^3$, m	
2.5–5	2.8	2.1	0.655	0.832
1.25–2.5	2.15	1.45	0.5	
0.63–1.25	1.15	0.95	0.355	
0.315–0.63	0.57	0.44	0.215	
0.14–0.315	0.31	0.17	0.07	
0.1–0.14	0.13	0.1	0.045	

The following characteristics of the stationary layer of wild carrot pomace were determined using the aforementioned methods:

- bulk density $\rho_b = 407$ kg/m^3;
- true density $\rho_t = 512$ kg/m^3;
- porosity of the layer $\varepsilon = 0.34$ m^3/m^3.

The results of experimental studies on pressure losses from the fictitious gas flow velocity at different heights of the stationary layer are shown in Fig. 3.

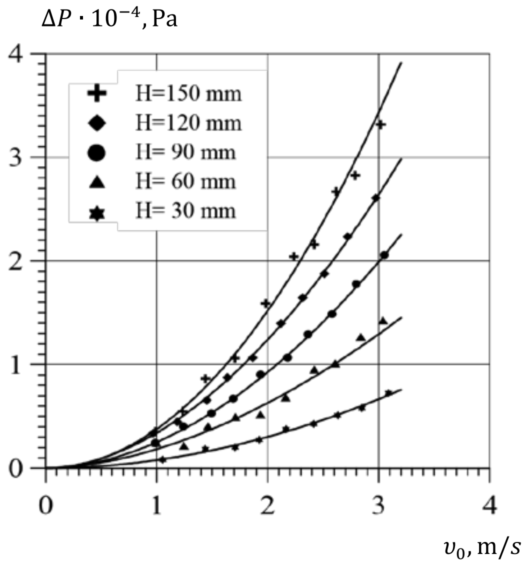

Fig. 3. Dependence of pressure drop ΔP in the stationary layer of wild carrot pomace on the height H at different filtration gas flow velocity values υ_0

As seen in Fig. 2, pressure losses increase with the height of the stationary layer. It should also be noted that the curves have a parabolic shape. This indicates that the hydraulic resistance of the investigated material is formed under the influence of both inertial and viscous components.

To generalize the obtained experimental results shown in Fig. 3, we will use the Darcy – Weisbach equation, presented in the form of a two-term equation (3). To this end, we will present the results of the conducted research shown in Fig. 1 a s a functional dependence $\frac{\Delta P}{(H \cdot \upsilon_0)}$. After approximating the experimentally obtained data with a linear relationship for the segment cutting the ordinate axis, the value of $A^* = A \cdot \frac{\mu \cdot a^2}{32 \cdot \varepsilon^3}$ was obtained, and by taking the tangent of the slope angle of the line, the value of $B^* = B \cdot \frac{\rho \cdot a}{8 \cdot \varepsilon^3}$ was derived. Thus, equation (3) takes the following form:

$$\frac{\Delta P}{H \cdot \upsilon_0} = 5000 + 22000 \cdot \upsilon_0. \quad (6)$$

The equation (5) within the investigated speed range can be used for predicting pressure loss values and selecting equipment during the filtration drying of wild carrot pomace.

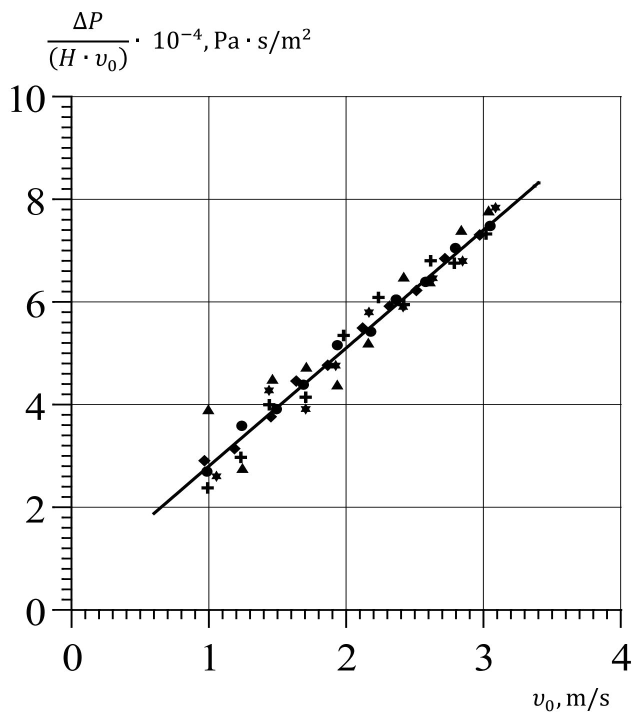

Fig. 4. Dependence $\frac{\Delta P}{H \cdot \upsilon_0} = f(\upsilon_0)$ for the stationary layer of wild carrot pomace (symbols correspond to those in Fig. 3)

3.1. External goal of hydrodynamics

To obtain the calculated dependencies in the form of dimensionless complexes, the experimental results presented in Fig. 3 were expressed as the relationship between the Euler number and the Reynolds number (Fig. 5). The analysis of Fig. 5 demonstrates that the Euler number depends on the height of the stationary layer of material, and the experimental data are well described by a power-law dependence. The curves for different heights are nearly parallel, and the distance between them is proportional to the height of the stationary layer.

Fitting the experimental data from Fig. 5 with a power function allowed for the determination of the exponent in the Reynolds number, which was –0.08 for all heights, while the coefficient *A* varied depending on the height. The obtained results are presented in Table 3.

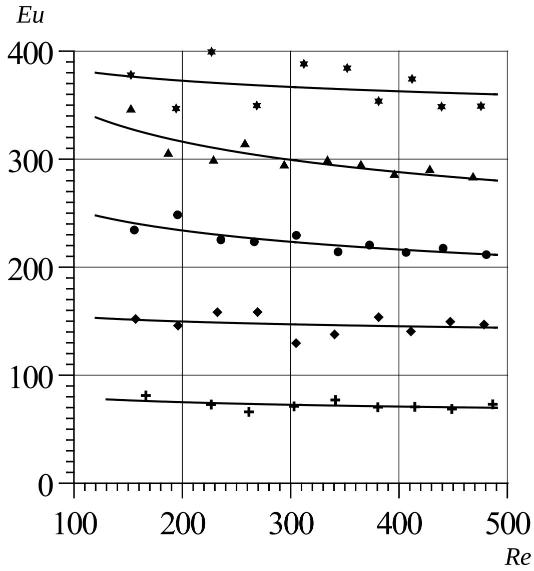

Fig. 5. Dependence of the Euler number on the Reynolds number for different heights of the stationary layer of wild carrot pomace (notations correspond to Fig. 3)

Table 3

The dependence of the unknown coefficients and the exponent on the height of the stationary layer of wild carrot pomace

H, m	0.15	0,12	0.09	0.06	0.03
H/d_p	182.34	145.87	109.40	72.93	36.47
A	580	480	360	230	115
n	–0.08				

To generalize the dependence for all investigated heights, a graph $A^* = f(H/d_p)$ is presented in Fig. 6. It was found that the determined coefficients *A* for each height lie on a straight line. Approximating these values with a power function allows for determining the coefficient A^* and the exponent for the geometric simplex (H/d_p), which is equal to one.

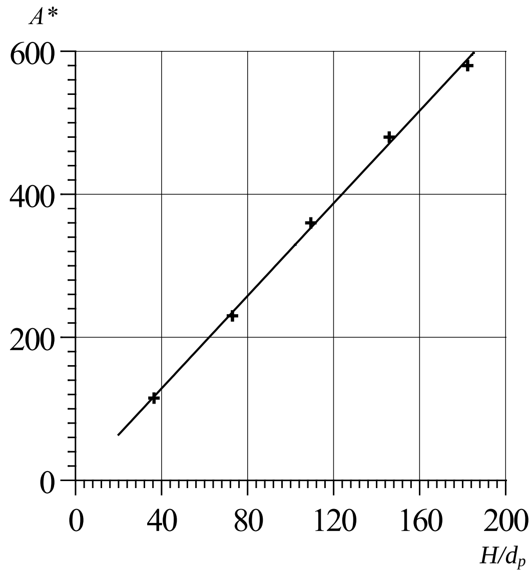

Fig. 6. Dependence of the coefficient A^* on the geometric simplex H/d_p

After summarizing the obtained data, equation (4) took the following form:

$$Eu_{\text{ext}} = 3.2 \cdot Re^{-0.08} \cdot \frac{H}{d_{\text{p}}} \quad (7)$$

This dependence holds true for Reynolds numbers ranging from 60 to 200. The absolute value of the relative error between the experimental and theoretically calculated values does not exceed 10 %.

3.2. Internal goal of hydrodynamics

The results of the experimental studies are presented as a functional dependence $Eu = f\left(\frac{H_e}{d_e}\right)$ for different values of the Reynolds number (Fig. 7). As can be seen from Fig. 7, the value of the Euler number increases with the increase in the geometric simplex, which leads to an increase in the slope angle of the line relative to the *y*-axis.

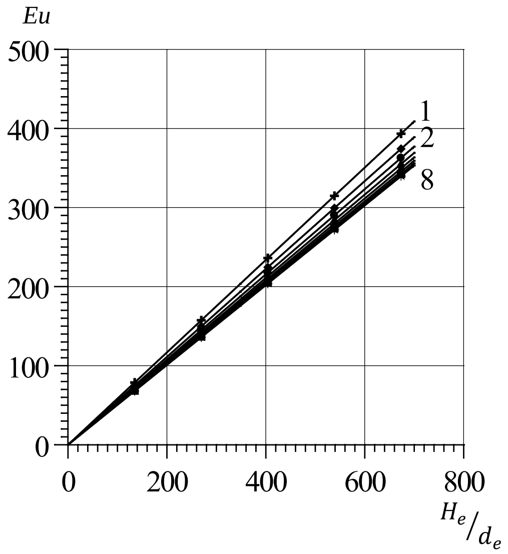

Fig. 7. Dependence of the Reynolds number on the geometric simplex $\frac{H_e}{d_e}$
1 – *Re* = 60; 2 – *Re* = 80; 3 – *Re* = 100; 4 – *Re* = 120; 5 – *Re* = 140;
6 – *Re* = 160; 7 – *Re* = 180; 8 – *Re* = 200

Therefore, to find the unknown coefficient "*A*", the dependence of the tangent of the slope angle of the line on the Reynolds number was constructed.

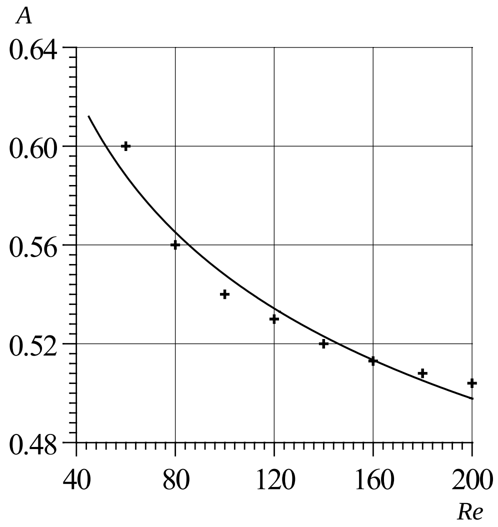

Fig. 8. Dependence of the coefficient *A* on the Reynolds number

For the internal goal of hydrodynamics, the following form of the equation (3) was obtained:

$$Eu = 1.04 \cdot Re^{-0.14} \cdot \frac{H_e}{d_e}\ . \qquad (8)$$

The absolute value of the maximum relative error between the values of the Euler number calculated from the experimental data and those obtained using the equation (7) does not exceed 9 %.

4. Conclusions

The study first investigates the internal and external hydrodynamics of the stationary layer of wild carrot pomace. Unknown coefficients of the Darcy – Weisbach equation, A* and B*, are determined for predicting pressure losses in the stationary layer of wild carrot pomace. Experimental data are generalized in the form of a dimensionless equation $Eu = A \cdot Re^x \cdot \left(\frac{H_e}{d_e}\right)^y$ for studying the internal hydrodynamics problem, and in the form of the equation $Eu = A \cdot Re^x \cdot \left(\frac{H}{d_p}\right)^y$ for the external hydrodynamics problem.

For the external hydrodynamics problem, the unknown coefficients are: A = 3.2, x = – 0.08, and for the internal problem: A = 1.04, x = – 0.14.

A comparison is made between the theoretically calculated data, obtained from equations (6), (7), and (8), and the data obtained experimentally.

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