CFD-Modeling of Thermal Agent Flow Through a Layer of Barley Brewer's Spent Grain

Roman Chyzhovych, Oleksandr Ivashchuk, Volodymyr Atamanyuk

Department of Chemical Engineering, Lviv Polytechnic National University, UKRAINE,
Lviv, 12 Bandery str., E-mail: roman.a.chyzhovych@lpnu.ua

***Abstract* – The paper contains the computer modeling results of the hydrodynamics of the thermal agent movement through a stationary layer of dried barley brewer's spent grain. To carry out the modeling, the characteristics of the porous zone were previously determined, including the layer porosity ε of the studied material, the values of the viscous 1/α and inertial C_2 resistance coefficients. Simulation was done in the ANSYS Fluent 2022 R2 software package using the k-ω SST turbulence model. The study was carried out for the researched heights of the dried brewer's spent grain layer in the range of H = 80÷120 mm at the thermal agent flow velocities w_0 = 0.83÷1.78 m/s. Based on the experimental data of the layer's hydraulic resistance, the average modeling error for all experimental points was calculated to be 6.85 %.**

Keywords – biomass, brewer's spent grain, drying, filtration drying, hydrodynamics, computer modeling, CFD.

Introduction

The secondary use of plant biomass is one of the most important areas of research, not only to find new application opportunities but also to improve and optimize existing ones. Rational environmental management will reduce the amount of accumulated plant waste at industrial production facilities and help to improve the overall environmental situation [1].

One of the waste products of plant origin that requires attention is barley brewer's spent grain, which is a by-product of industrial beer production [2, 3]. One of the characteristics of brewer's spent grain that limits its possible secondary use is the high residual moisture content of the product (~70 % wt.) after the technological process [4, 5]. This factor leads to rapid spoilage of this by-product (~2÷3 days) [6].

Given the above, the existing areas of barley brewer's spent grain secondary use require partial or complete drying, including: food additives for bakery products [3, 7], fertilization of agricultural land [8], raw materials for biogas production [3, 9], production of solid fuel briquettes [6], etc.

For the drying of barley brewer's spent grain, it is proposed to use a highly efficient method of filtration drying, given its advantages [10] for drying dispersed materials of plant origin in a stationary layer.

A preliminary study of the flow hydrodynamics of the thermal agent movement through a stationary layer of the studied material will allow for determining its hydraulic resistance. The data obtained are necessary for the design and calculation of drying equipment to predict the energy costs of creating a pressure difference during the drying of dispersed material. Processing of the obtained experimental data on the hydrodynamics of the thermal agent movement will make it possible to conduct computer modeling of the process to predict the hydraulic resistance of different heights of the barley brewer's spent grain stationary layer.

Experimental part

To carry out experimental studies of the hydrodynamics of thermal flow movement through a stationary layer of dispersed material, barley brewer's spent grain produced on the production line of the "Kumpel" brewery (Lviv, Ukraine) was used.

To remove excess humidity from the initial plant material, barley brewer's spent grain was previously dried by filtration drying in an experimental laboratory installation [11].

The hydrodynamics of the thermal agent's movement through the layer of dried barley brewer's spent grain was studied to determine the influence of the fictitious speed w_0 of the thermal agent on the value of the hydraulic resistance ΔP of the stationary layer of the studied material. To determine the stationary layer resistance of the material, the resistance of the cylindrical container's perforated baffle (Fig. 1) of the laboratory filtration drying installation was additionally determined [11]. The hydraulic resistance of the dried barley brewer's spent grain layer was calculated as the difference between the full experimentally obtained value and the value calculated from the polynomial equation for each value of the air flow rate studied.

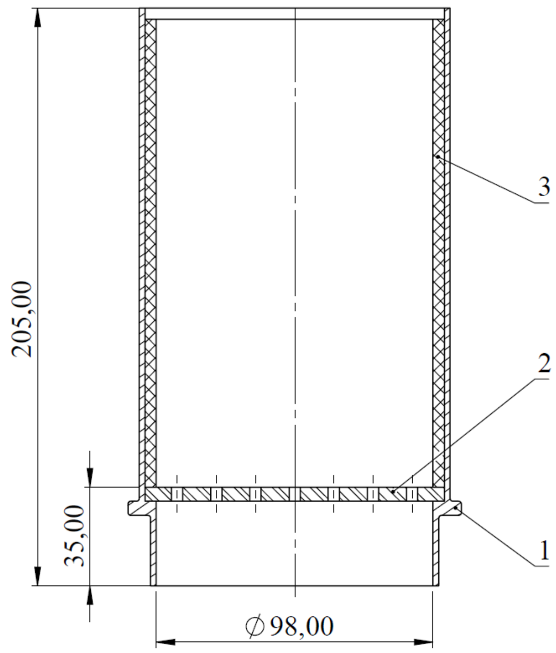


Fig. 1. Schematic representation of a cylindrical container: 1 – container body, 2 – perforated baffle, 3 – thermal insulation insert.

To control the layer height of the dispersed material in a cylindrical container (Fig. 1), the bulk density of the barley brewer's grain was determined according to the methodology of [12], which was 175.2 kg/m^3. Also, the value of the layer porosity was experimentally determined in accordance with [12], which for dried raw materials was 0.32 m^3/m^3. The average moisture content of the material was 12.69 % wt.

Results and discussion

According to the recommendation of [13], the porous media method in the ANSYS Fluent software package was used to carry out a computer simulation of the thermal agent's movement through the dispersed layer of the research material. The process was modeled on the basis of the system of Navier-Stokes differential equations and the flow continuity equation with the additional use of the Darcy equation to determine the value of the layer hydraulic resistance ΔP [13, 14].

To carry out computer modeling, in addition to the parameters of the dispersed raw material, it is necessary to take into account the parameters of the thermal agent flow. Air was used as a thermal agent, the temperature of which was 17 °C at the time of the series of experiments.

The experimental data of the hydrodynamics study of the thermal agent movement through a stationary layer of dried brewer's spent grain are given in the form of a graphical dependence of the influence of the fictitious flow rate w_0 on the change in the hydraulic resistance ΔP of the studied material layer (Fig. 2).

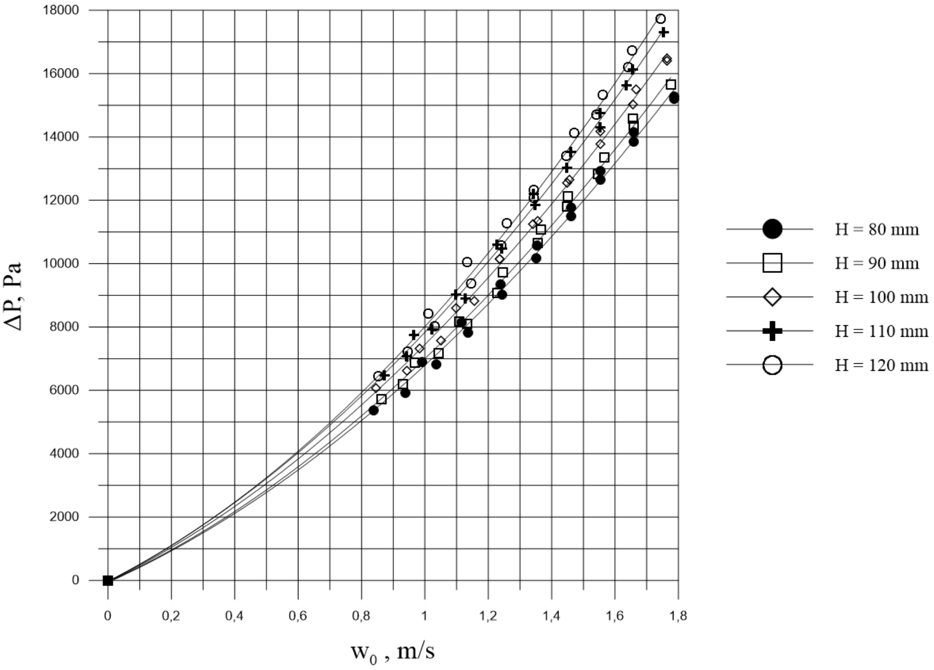


Fig. 2. Changes in the hydraulic resistance of the dried brewer's spent grain layer depending on the fictitious speed of the thermal agent at different layer heights (T = 17 °C, H = 80÷120 mm, w_0 = 0.83÷1.78 m/s).

Using the obtained experimental data on the hydrodynamics of the thermal agent movement through the layer of the studied material, a graphical dependence was plotted (Fig. 3) using the linear equation (1) obtained from the Darcy-Weisbach equation [15]:

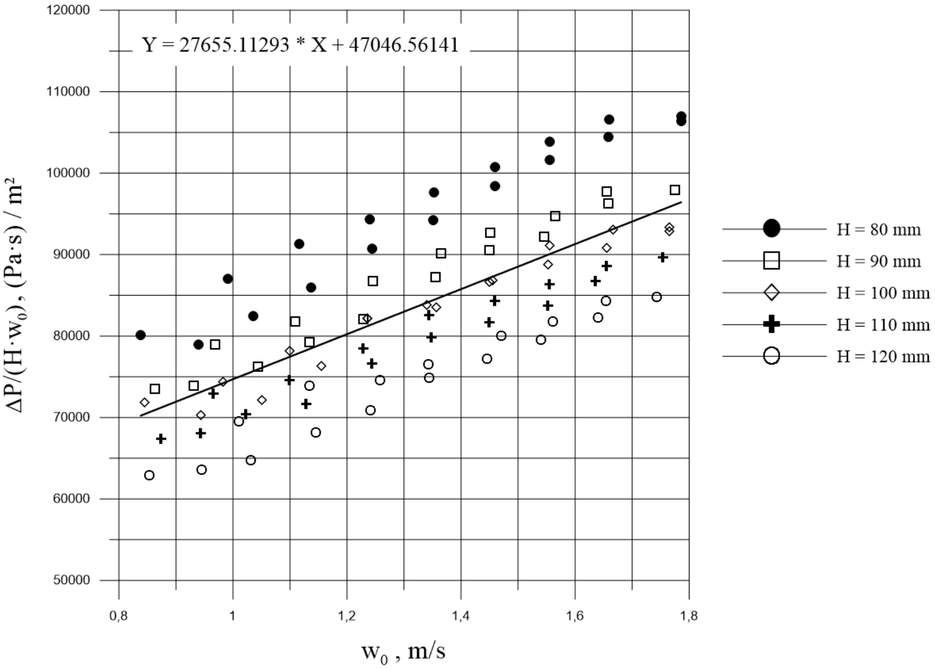


Fig. 3. Graphical dependence of $\Delta P/(H \cdot w_0)=f(w_0)$ for the studied layer heights (T = 17 °C, H = 80÷120 mm, w_0 = 0.83÷1.78 m/s).

$$\frac{\Delta P}{H \cdot w_0} = A^* + B^* \cdot w_0 \quad (1)$$

where ΔP – hydraulic resistance of the material layer, Pa; H – height of the material layer, m; w_0 – fictitious velocity of the thermal agent, m/s; A^* and B^* – the coefficients of the equation.

Comparing the obtained linear dependence (Fig. 3) and equation (1), it is clear that the coefficients A^* and B^* will correspond to the coefficients in the equation of the straight line obtained from the experimental data of the thermal agent hydrodynamics.

For computer modeling using the porous media method, it is necessary to determine the coefficients of viscous $1/\alpha$ and inertial C_2 resistances, which can be calculated based on the straight-line equation (Fig. 3) and the physical parameters of the thermal agent using dependencies (2) and (3) [12, 13]:

$$A^* = \frac{\mu}{\alpha} \quad (2)$$

$$B^* = C_2 \frac{1}{2} \rho \quad (3)$$

where μ – coefficient of dynamic viscosity of the thermal agent, Pa·s; ρ – thermal agent density, kg/m^3.

Computer simulations of the movement of thermal flow through a layer of dispersed material were carried out in the *ANSYS Fluent 2022 R2* program using the *k-ω SST* turbulence model, according to the recommendations of [12, 16]. The characteristics of the porous modeling zone were determined by the value of the porosity of the dried brewer's grains layer ε and the values of the viscous $1/\alpha$ and inertial C_2 resistance coefficients, which are $2.63 \cdot 10^9$ m^{-2} and 45448 m^{-1}, respectively.

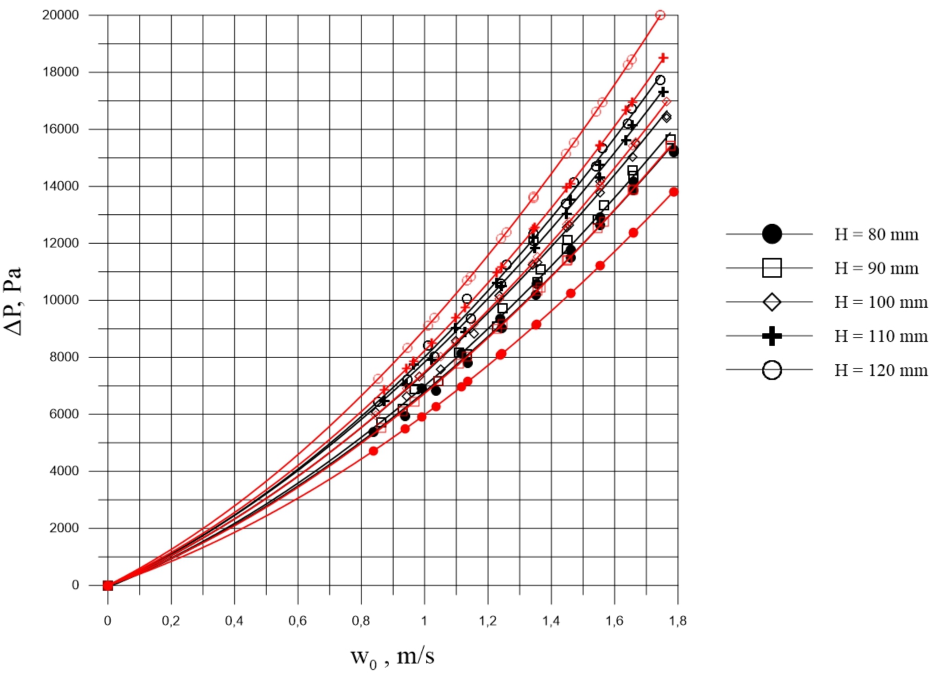


Fig. 4. Graphical comparison of the obtained modeling values (—— red lines) of hydraulic resistance with the experimental values (—— black lines) (T = 17 °C, H = 80÷120 mm, w_0 = 0.83÷1.78 m/s).

As a result of the simulation, the hydraulic resistance values of the studied material's stationary layer were obtained for each experimental fictitious velocity of the thermal agent. To compare the obtained simulation data with the experimental ones, a graphical dependence of the change in hydraulic resistance ΔP on the fictitious speed w_0 was plotted (Fig. 4).

Analyzing the obtained graphical dependences shown in Fig. 4, we observe a certain deviation of the obtained modeling results from the experimental ones as the difference in layer heights increases relative to the average layer height of the studied range. In view of this, to improve the accuracy of modeling, it is recommended to carry out studies for narrower ranges and, accordingly, with a smaller step of layer heights of the studied dispersed material.

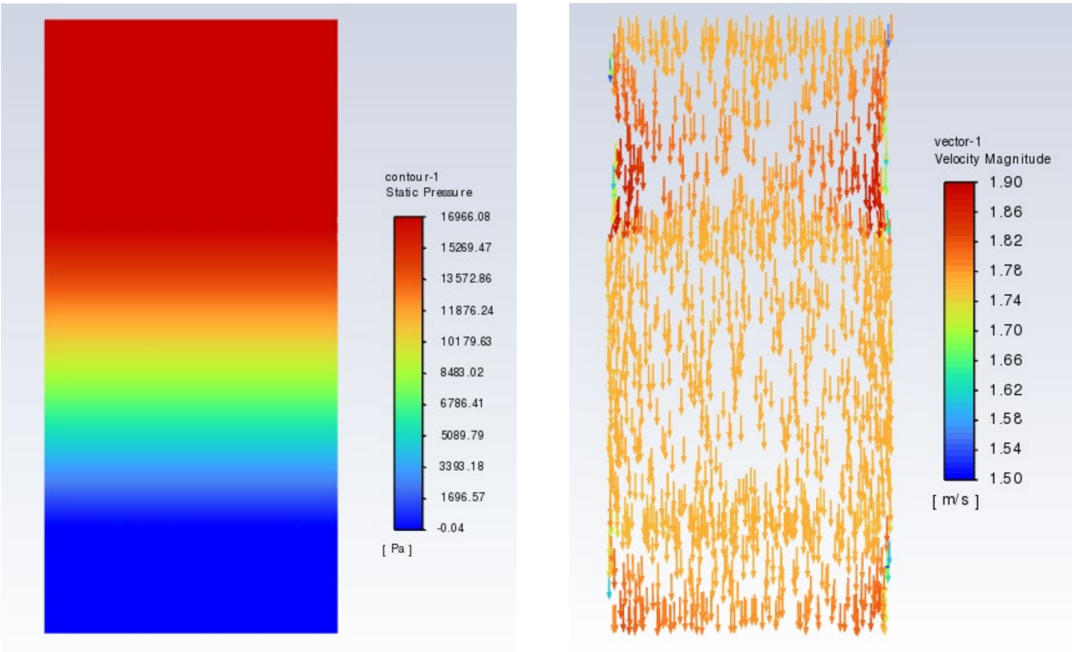
The calculated modeling errors relative to the experimental data are given in Table 1, in the form of separate values for each studied layer height and their generalized value for all points of the experiment.

Table 1

Relative errors of the computer modeling for the studied heights of the dried brewer's spent grain layer H = 80÷120 mm

Material layer height, mm	Average modeling error, %
80	11.22
90	3.26
100	1.88
110	5.74
120	12.12
Average value:	6.85

Analyzing the data from Table 1, the highest average value of the relative error is observed for the layer height H = 80 mm. If we take into account all the points of the modeling, the average error is 6.85 %.



a b

Fig. 5. An example of visualization of the static pressure field distribution (a) and vector velocity field distribution (b) in the cross-section plane of the modeling area for H = 100 mm, w_0 = 1.76 m/s.

To visualize the character of the thermal agent's movement through the stationary layer of the studied material, the simulation results were output in the distribution of a static pressure field (Fig. 5, a) and a vector velocity field (Fig. 5, b) in the cross-section plane of the calculation area.

Analyzing the visualization of the static pressure field distribution (Fig. 5, a), we observe a gradual decrease in static pressure along the path of the thermal agent flow through the modeling area, as well as its constant value in the zones above and below the material layer. At the same time, the vector distribution of the velocity field (Fig. 5, b) indicates the straight-line character of the thermal agent's movement along the modeling area. Also, its decrease is observed near the walls of the modeling area and at the entrance to the porous zone.

Conclusions

Computer simulations of the hydrodynamics of the thermal agent's movement through a layer of dried barley brewer's spent grain in a stationary state were done using the *ANSYS Fluent 2022 R2* software package. The study was carried out for a range of dried barley brewer's spent grain layer heights $H = 80 \div 120$ mm and thermal agent velocities $w_0 = 0.83 \div 1.78$ m/s.

The parameters of the studied raw materials were experimentally determined, including the bulk density of 175.2 kg/m^3 and the porosity of 0.32 m^3/m^3.

The simulation results are given in the form of a graphical dependence on the influence of the fictitious heat transfer agent velocity on the hydraulic resistance of the dispersed material layer. The simulation data are compared with those previously obtained experimentally and the relative errors between them are calculated. Based on the experimental data of the hydraulic resistance of the layer, the average modeling error for all experimental points was calculated, which is 6.85 %. To improve the accuracy of modeling, it is recommended to carry out studies for narrower boundaries and with a smaller step in the layer height of the dispersed material.

Visualizations of the distribution of the static pressure field and the vector velocity field in the cross-section plane of the modeling area are obtained, and the nature of the change in static pressure and velocity along the airflow path is analyzed.

Computer modeling of the process under study will make it possible to predict the value of the hydraulic resistance of the dried barley brewer's spent grain layer for the studied height limits, which is necessary for the design and calculation of drying equipment to predict the energy costs of creating a pressure difference during the drying of dispersed material.

Acknowledgment

Authors are expressing their gratitude to CADFEM UA LLC, the official distributor of Ansys Inc. in Ukraine, for help with the software licensing.

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