

## Mathematical modeling and optimization of dry fractionation of wheat flour in a pneumatic screw classifier

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### ABSTRACT

This study presents the development and experimental verification of a mathematical model for the dry fractionation of wheat flour in a pneumatic screw classifier. The model describes the distribution of axial, radial, and tangential airflow components and accounts for the effects of the adjustable aperture opening degree ( $\varphi$ ) and material loading coefficient on particle transport and separation. Particle motion was analyzed based on the balance among aerodynamic drag, gravitational, and centrifugal forces, together with particle residence-time and radial-migration conditions. Engineering calculations were performed for a classifier throughput of 150 kg/h, corresponding to a material mass flow rate of 0.0417 kg/s and a material loading coefficient of approximately  $\mu = 0.029$ . The theoretically predicted effective separation window was  $0.188 \leq \varphi \leq 0.477$ . Experimental studies were conducted over the aperture-opening range  $\varphi = 0.10$ – $0.90$ , and classifier performance was evaluated using fraction yields, normalized purity indices, enrichment selectivities, overall selectivity, recovery selectivity, and fractionation efficiency. Although the individual performance indicators attained their maximum values at different aperture openings, multi-criteria evaluation identified  $\varphi = 0.30$ – $0.40$  as the most favorable operating range. Within this interval, the intermediate fraction yield was minimized to 17.19–17.57%, while the normalized protein purity index in the light fraction remained within 93.01–93.99%, the normalized starch purity index in the heavy fraction within 95.83–96.52%, overall selectivity within 3.946–3.959, and fractionation efficiency within 78.49–78.92%. Quantitative comparison between calculated and experimental results demonstrated close agreement for all investigated indicators. The coefficients of determination ranged from 0.998 to 1.000, while the mean absolute percentage error did not exceed 4.56%. The highest relative errors were observed in the light and intermediate fraction yields, whereas the normalized purity and selectivity indices were predicted with errors of no more than 0.14%. The proposed model provides a compact engineering tool for evaluating airflow–particle interactions, selecting favorable operating conditions, and optimizing pneumatic screw classifiers to produce protein- and starch-enriched wheat flour fractions.

**Keywords:** wheat flour; pneumatic screw classifier; dry fractionation; airflow distribution; aperture opening degree; material loading coefficient; normalized purity index; fractionation efficiency.

### INTRODUCTION

Wheat flour is one of the most important raw materials in the food industry, and the main components in its composition are starch and protein

[1–4]. In recent years, due to the increase in demand for plant-based proteins, the issue of separating protein fractions in flour has become particularly relevant [5,6]. Protein-rich concentrates are widely used in the production of bakery and

confectionery products, functional foods, and protein supplements. In addition, starch-rich fractions are also important raw materials in the fields of food, pharmaceuticals, and biotechnology [7–9].

Traditionally, moisture processing technologies are used to separate protein and starch. The main disadvantages of such methods are considered to be high water and energy consumption, wastewater generation, and the need for drying operations. In recent years, there has been a significant increase in interest in dry fractionation technology. Among the methods of dry fractionation, pneumatic classification is considered one of the methods that require less energy, are environmentally safe, and are industrially efficient [10–12].

The process of pneumatic classification is based on the difference in the aerodynamic properties of the particles [13]. Flour particles move along different trajectories under the influence of airflow, resulting in the formation of a light fraction rich in protein and a heavy fraction rich in starch. The efficiency of the process depends on the apparatus design, airflow parameters, and the particles' physical and mechanical properties [14–16].

At present, various mathematical models have been proposed to describe the processes of dry fractionation and pneumatic classification of flour. In most studies, particle motion is characterized by aerodynamic properties, and the separation process is characterized by comparing airflow velocity with particles' terminal or critical velocities [17,18]. Such models are often designed for vertical pneumatic separators and cyclone classifiers and are based on the interaction between particle gravity and aerodynamic drag [19,20].

In some studies, particle motion has been treated as one- or two-dimensional flow, and the efficiency of separation has been linked to changes in airflow. However, in such models, the spatial structure of airflow within the apparatus is insufficiently described. In particular, the relationship between air movements in axial, radial, and tangential directions is not taken into account [21,22].

In recent years, computational fluid dynamics (CFD)-based models have been widely used. Although CFD models enable high-precision depiction of airflow distribution, they require substantial computational resources and are not always suitable for operational engineering evaluation of the apparatus's operating modes [23–25]. In addition, in such models, the effects of adjustable suction zones and of the material load on the apparatus are not fully considered [26–28].

An analysis of the literature reveals several limitations of existing models: airflow is often treated as unidirectional; the interactions among axial, radial, and tangential flow components governing particle motion are insufficiently described; the effects of adjustable openings in the central tube and material loading on the aerodynamic regime are frequently neglected; and engineering criteria for identifying the effective separation region remain inadequately developed. Therefore, a comprehensive investigation of airflow structure and the effects of the degree of aperture opening and material loading is of both scientific and practical importance [29, 30].

Recent studies have also emphasized the importance of airflow distribution and particle aerodynamic behavior in dry fractionation systems. In particular, the mathematical modeling approach reported in [31] demonstrated that airflow control is a key factor affecting separation efficiency and product purity. However, the influence of adjustable suction openings and material loading on the effective separation window of pneumatic screw classifiers remains insufficiently investigated. Therefore, further research is required to develop engineering models that predict optimal operating conditions.

The purpose of the work is the mathematical modeling of the distribution of airflows in a pneumatic screw classifier for fractionating wheat flour, determining the effect of the degree of opening and material loading on aerodynamic conditions, as well as theoretical substantiation of optimal parameters that ensure effective separation of protein and starch fractions.

In contrast to conventional pneumatic classification models, which primarily rely on one-dimensional airflow analysis and particle terminal velocity, the proposed model provides a comprehensive description of the axial, radial, and tangential airflow components in a pneumatic screw classifier. In the proposed model, the aperture opening degree ( $\varphi$ ) and the material loading coefficient ( $\mu$ ) are incorporated into the mathematical formulation, enabling the influence of both design and operating parameters on particle separation in a two-phase air-particle system to be evaluated.

A further novelty of the study is the introduction of the concept of a “separation window”, which defines the effective operating region of the classifier as the simultaneous fulfillment of light-particle entrainment and heavy-particle retention conditions. The validity of the proposed

approach was confirmed experimentally, and the theoretically predicted separation region ( $0.188 \leq \varphi \leq 0.477$ ) showed good agreement with the experimentally determined optimum operating range ( $\varphi = 0.30\text{--}0.40$ ).

## MATERIALS AND METHODS

### Raw material characteristics

Commercial wheat flour of the highest grade produced in the Republic of Kazakhstan was used as the raw material for this study. Since the physical, chemical, and structural properties of flour significantly influence pneumatic classification efficiency, its main characteristics were determined prior to the experiments [32].

The moisture content of the flour was  $13.5 \pm 0.3\%$ , crude protein content was  $12.8 \pm 0.2\%$ , and starch content was  $70.5 \pm 0.5\%$ . The bulk density of the material was  $540 \pm 15 \text{ kg/m}^3$ .

Particle size analysis showed that most particles were distributed between 20 and 80  $\mu\text{m}$ , with an average equivalent particle diameter of  $48 \pm 5 \mu\text{m}$ . The fraction of fine particles ( $<40 \mu\text{m}$ ) was approximately 32%, medium-sized particles (40–80  $\mu\text{m}$ ) accounted for 51%, and coarse particles ( $>80 \mu\text{m}$ ) represented 17% of the total sample.

According to literature data, protein-rich particles generally have smaller particle sizes and different aerodynamic characteristics than starch granules. Consequently, during pneumatic classification, smaller and lighter protein particles tend to be transferred into the light fraction, whereas larger and denser starch particles are predominantly concentrated in the heavy fraction.

The physical and granulometric characteristics of the flour were used as input parameters

for the mathematical model, engineering calculations, and interpretation of experimental results.

The values presented in Table 1 characterize the initial wheat flour before pneumatic fractionation. Fresh flour used to compensate for sampling and handling losses was taken from the same initial batch.

### Description of the unit for flour fractionation

Figure 1 shows a general view of the wheat flour separation plant into light, medium, and heavy fractions. The flour from the hopper is fed to the dispenser, which ensures uniform dosing and feeding to the pneumatic classifier. The airflow from the fan carries the particles into the working zone, where they are separated into light, medium, and heavy fractions based on their aerodynamic properties. The resulting fractions are transported to the corresponding cyclones for collection [33].

### Construction of a pneumatic-screw classifier

The design of the pneumatic screw classifier is shown in Figure 2 [27]. The apparatus consists of a spiral pneumatic channel, a perforated central tube with adjustable openings, and fraction discharge outlets. The adjustable openings regulate airflow distribution and particle separation conditions within the classifier.

Of the pneumatic screw classifier. The operating principle of the pneumatic screw classifier is based on differences in the aerodynamic properties of particles. Flour particles are introduced into the spiral pneumatic channel by a tangential airflow, where they are subjected to aerodynamic, gravitational, and centrifugal forces. Light particles with lower density and smaller size are entrained in the central tube and collected as a protein-rich fraction. In contrast, larger and denser particles move toward the outer wall and are discharged as a starch-rich fraction. Partially separated particles are collected as an intermediate fraction. The separation efficiency is controlled by adjusting the degree of opening of the central tube slots, thereby regulating airflow distribution, particle residence time, and fractionation conditions.

### Experimental procedure

Experimental verification of the proposed mathematical model was performed using the

**Table 1.** Physical and granulometric characteristics of the initial wheat flour

| Parameter                               | Value                       |
|-----------------------------------------|-----------------------------|
| Moisture content                        | $13.5 \pm 0.3\%$            |
| Crude protein content                   | $12.8 \pm 0.2\%$            |
| Starch content                          | $70.5 \pm 0.5\%$            |
| Bulk density                            | $540 \pm 15 \text{ kg/m}^3$ |
| Average particle diameter               | $48 \pm 5 \mu\text{m}$      |
| Fine particles ( $< 40 \mu\text{m}$ )   | 32%                         |
| Medium particles (40–80 $\mu\text{m}$ ) | 51%                         |
| Coarse particles ( $> 80 \mu\text{m}$ ) | 17%                         |

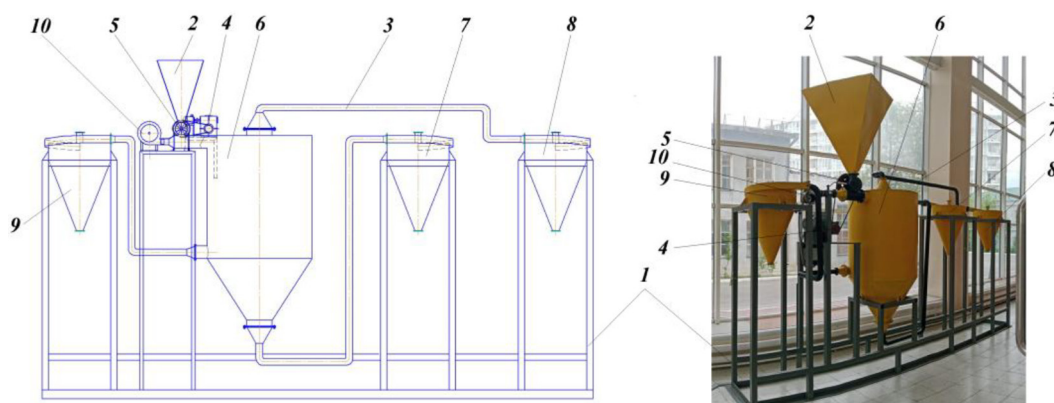
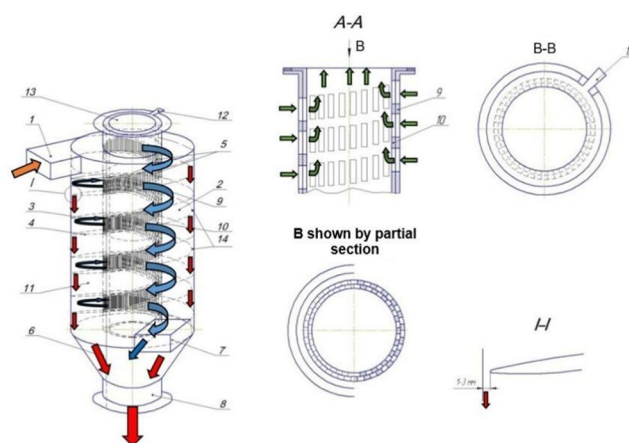


**Figure 1.** General view of the pneumatic screw classification system for wheat flour fractionation. 1 – standing; 2 – body; 3 – pipelines for transporting flour fractions; 4 – flour measuring (doser) drive; 5 – meter (doser); 6 – pneumatic classifier; 7 – cyclone for heavy flour fractions; 8 – cyclone for light flour fractions; 9 – cyclone for medium flour fractions; 10 – fan



- - the movement direction of the total air consumption ( $Q_{tot}$ ) supplied to the device through the fan,  $m^3/sec$
- - the movement direction of the air consumption ( $Q_{core}$ ) spent on transporting the lightweight flour fractions upward through the longitudinal openings with adjustable openings,  $m^3/sec$
- - the movement direction of the air consumption ( $Q_{ann}$ ) spent on transporting the medium weight flour fractions, moving through the annular space formed by the outer cylinder and the central pipe,  $m^3/sec$
- - direction of movement of airflow ( $Q_{ann}$ ) spent on transportation of heavy flour fractions passing through the opening between the lower rotating surface and the cylindrical part of the stand,  $m^3/sec$

**Figure 2.** Scheme of a pneumatic-screw classifier. 1 – pipe for feeding flour to pneumatic classifier; 2 – pneumatic channel; 3 – upper spiral surface; 4 – lower spiral surface; 5 – openings; 6 – cone-shaped part of the structure; 7 – tube pipe; 8 – tube of growth; 9 – central pipe in the form of a hollow cylinder; 10 – a pipe for adjusting the size of the holes; 11 – cylindrical part of the structure; 12 – a handle for adjusting the size of the holes; 13 – a large pipe for extracting small fraction; 14 – hole

pneumatic screw classifier shown in Figures 1 and 2. Before each experimental run, the classifier was operated without material until stable airflow conditions were established. Wheat flour was then continuously supplied to the classifier by a screw feeder at a constant mass flow rate of 150 kg/h, ensuring uniform material loading throughout the experiment.

The aperture opening degree ( $\phi$ ) was varied from 0.10 to 0.90 in increments of 0.10, while

the total airflow rate, classifier geometry, tangential airflow velocity, and flour feed rate were maintained constant. Each experimental run lasted 3–10 min, corresponding to a nominal processed-material throughput of approximately 7.5–25.0 kg per run.

During each run, flour was continuously supplied at the specified feed rate. After the predetermined operating period, feeding was stopped, and the light, intermediate, and heavy fractions

were collected separately from their corresponding receivers and weighed. The measured fraction masses were used to calculate the yields of the three fractions and to assess the material balance before representative samples were taken for compositional analysis.

After weighing and sampling, the remaining portions of the light, intermediate, and heavy fractions were recombined and thoroughly homogenized to obtain a reconstituted feed mixture. Fresh flour from the same initial batch was added only in an amount corresponding to material losses associated with sampling, collection, and handling, thereby restoring the required feed mass for the subsequent experimental run. The reconstituted and replenished flour mixture was then reused in the following runs.

Therefore, the processed-material throughput of 7.5–25.0 kg per run does not represent an equivalent consumption of fresh wheat flour. Most of the separated material was recombined and reused, while fresh flour was added only to compensate for documented material losses.

Protein and starch contents in the collected fractions were determined using the Kjeldahl method (GOST 10846-91) and the Ewers polarimetric method (GOST 10845-98), respectively. The analytical results were subsequently used to calculate the normalized purity indices, component recoveries, enrichment selectivities, overall selectivity, recovery selectivity, and fractionation efficiency.

Each aperture opening degree was evaluated in at least three repeated experimental runs under identical operating conditions. Before each subsequent run, the recombined material and the added fresh flour were thoroughly homogenized to ensure a uniform feed mixture. The reported values represent the arithmetic means of the repeated measurements. The experimental results were compared with the calculated values to verify the adequacy of the proposed mathematical model and to identify the most favorable multi-criteria operating range of the pneumatic screw classifier.

## Aerodynamic model

The efficiency of the pneumatic classification process depends on the airflow structure inside the apparatus and its interaction with particles. Therefore, the operation of the pneumatic classifier is described using an aerodynamic model.

In the proposed model, airflow consists of axial, radial, and tangential components. The axial

flow transports particles along the apparatus, the radial flow moves them toward the central pipe, and the tangential flow affects particle separation.

The total airflow rate is distributed between the central pipe and the annular zone:

$$Q_{tot} = Q_{core} + Q_{ann} \quad (1)$$

where:  $Q_{tot}$  is the total airflow rate,  $Q_{core}$  is the airflow entering the central tube, and  $Q_{ann}$  is the airflow in the annular zone.

$$Q_{core} = Q_{leak} + k\varphi(Q_{tot} - Q_{leak}) \quad (2)$$

where:  $Q_{core}$  is the airflow entering the central tube,  $Q_{leak}$  is the leakage airflow,  $k$  is the proportionality coefficient, and  $\varphi$  is the aperture opening degree.

Axial air velocity in the annular zone is determined by the ratio of airflow to the cross-sectional area of the annular channel:

$$U_{ax,ann} = \frac{Q_{ann}}{A_{ann}} \quad (3)$$

where:  $A_{ann} = \pi(R^2 - r^2)$  is the cross-sectional area of the annular channel.

The particle residence time is calculated as:

$$t_{res} = \frac{L_{path}}{U_{ax,ann}} \quad (4)$$

where:  $L_{path}$  is the particle travel path length along the spiral channel.

Light fractions are pumped through the longitudinal openings located in the central pipe. The radial velocity of the airflow through these openings is:

$$v_s = \frac{Q_{core}}{A_{cap}} \quad (5)$$

where:  $A_{cap} = 2\pi r_{core} L_{sl}$  is the effective area of the slotted openings in the central tube.

The time required for the particle to reach the central pipe:

$$t_{need} = \frac{\Delta r_{core}}{v_s} \quad (6)$$

Light particles are captured by the central tube when the residence time exceeds the radial migration time:

$$t_{res} \geq \frac{\Delta r_{core}}{v_s} \quad (7)$$

where:  $\Delta r_{core}$  is the radial distance from the particle trajectory to the central tube.

Centrifugal acceleration is applied to the particles by the rotating airflow in the device. Centrifugal acceleration in the case of tangential speed  $u_t$ :

$$a_c = \frac{u_t^2}{r_m} \quad (8)$$

where:  $u_t$  is the tangential airflow velocity (m/s), and  $r_m$  is the mean radius of the annular channel.

The presented aerodynamic model describes the airflow distribution in the pneumatic classifier, particle trajectories, and the separation mechanism. The main control parameters of the model are airflow, the degree of hole opening, axial and radial velocities, and the intensity of tangential flow. The analysis of the relationship between these parameters serves as the basis for determining effective operating modes and optimizing fractionation.

### Model input parameters

The principal input parameters and coefficients adopted in the mathematical model are summarized in Table 2.

For a flour feed rate of 150 kg/h, the material mass flow rate was 0.0417 kg/s. At a total airflow rate of 1.2 m<sup>3</sup>/s and an air density of 1.2 kg/m<sup>3</sup>, the airflow mass flow rate was 1.44 kg/s, resulting in a material loading coefficient of  $\mu = 0.029$ .

### Force balance and particle movement dynamics

In a pneumatic classifier, particles are divided into fractions as a result of the interaction

of forces that affect their movement in the airflow. Aerodynamic force, gravity, and centrifugal force act on every particle that moves inside the apparatus. The ratio of these forces determines whether the particle belongs to the light or heavy fraction.

To describe the movement of a particle, the balance of forces acting on it is considered.

#### Aerodynamic force

Airflow exerts drag or lift on the particle. This force is proportional to the square of the air speed:

$$F_d = \frac{1}{2} C_d \rho_a A_p (V - u)^2 \approx \frac{1}{2} C_d \rho_a A_p V^2 \quad (9)$$

where:  $F_d$  is the aerodynamic drag force,  $C_d$  is the drag coefficient,  $\rho_a$  is the air density,  $A_p$  is the projected particle area, and  $V-u$  is the relative particle velocity.

#### Gravitational force

The main force affecting the downward movement of a particle is the gravitational force:

$$F_g = m_p g \quad (10)$$

where:  $F_g$  is the gravitational force,  $m_p$  is the particle mass, and  $g$  is the gravitational acceleration.

#### Centrifugal force

In the pneumatic classifier, the airflow moves in a rotational direction, causing particles to experience a centrifugal force:

$$F_c = m_p \frac{u_t^2}{r} \quad (11)$$

where:  $F_c$  is the centrifugal force,  $u_t$  is the tangential airflow velocity, and  $r$  is the particle rotation radius.

**Table 2.** Parameters and coefficients used in the mathematical model

| Parameter       | Value                  | Basis for Selection                                                                       |
|-----------------|------------------------|-------------------------------------------------------------------------------------------|
| $Q_{tot}$       | 1.2 m <sup>3</sup> /s  | Rated fan airflow capacity                                                                |
| $Q_{leak}$      | 0.05 m <sup>3</sup> /s | Residual airflow through structural clearances                                            |
| $k$             | 0.35                   | Determined from the geometry of the adjustable openings                                   |
| $\mu$           | 0.029                  | Calculated from the flour feed rate of 150 kg/h and the airflow mass flow rate            |
| $C_d$           | 0.9                    | Adopted for irregularly shaped flour particles based on published data                    |
| $u_t$           | 3 m/s                  | Measured operating tangential airflow velocity                                            |
| $\beta, \gamma$ | 0.8; 0.5               | Empirical correction coefficients accounting for unresolved gas–solid interaction effects |

A separation criterion is introduced based on the ratio of aerodynamic force to the sum of gravitational and centrifugal forces:

$$K = \frac{F_d}{F_g + F_c} \quad (12)$$

where:  $K$  is the separation criterion, values of  $K > 1$  indicate particle entrainment by the airflow, whereas  $K < 1$  corresponds to particle settling.

### Critical entrainment velocity

The critical particle velocity is determined from the force balance condition:

$$F_d = F_g + F_c \quad (13)$$

The critical air velocity of the particle is determined from this equation:

$$V_{cr} = \sqrt{\frac{2m_p}{C_d \rho_a A_p} \left( g + \frac{u_t^2}{r} \right)} \quad (14)$$

where:  $V_{cr}$  is the critical particle velocity.

If  $V < V_{cr}$ , the particle settles, whereas if  $V > V_{cr}$ , it is entrained by the airflow.

Since protein-rich particles are generally smaller and less dense than starch-rich particles, their critical velocity is lower:

$$V_{cr,P} < V_{cr,S} \quad (15)$$

where:  $V_{cr,P}$  is the critical velocity of protein particles and  $V_{cr,S}$  is the critical velocity of starch particles.

Therefore, for effective fractionation, the operating velocity should satisfy the following condition:

$$V_{cr,P} < V_{op} < V_{cr,S} \quad (16)$$

This velocity range corresponds to effective fractionation conditions, where protein-rich particles are entrained into the light fraction while starch-rich particles remain in the heavy fraction.

### Effect of material loading

Under industrial operating conditions, the airflow contains a dispersed solid phase. Therefore, the material mass flow rate was incorporated into the model to better describe pneumatic classification.

To account for real operating conditions, the influence of the solid phase on airflow was

incorporated through the material loading coefficient ( $\mu$ ), which modifies the effective axial and radial airflow velocities in the two-phase air-particle system.

First, the mass flow rate of the air supplied to the device is determined:

$$m_{air} = \rho_{air} Q_{tot} \quad (17)$$

where:  $\rho_{air}$  is the air density, and  $Q_{tot}$  is the total airflow rate.

Denoting the mass flow rate of the product entering the device as  $m_s$ , the material load coefficient is determined by the following expression:

$$\mu = \frac{m_s}{m_{air}} \quad (18)$$

where:  $\mu$  is the material loading coefficient,  $m_s$  is the material mass flow rate, and  $m_{air}$  is the airflow mass flow rate.

The presence of particles reduces the effective airflow velocity and therefore requires correction of the axial and radial velocity components. As a result, the effective axial velocity determined by Equation 19 decreases and can be expressed as follows:

$$U_{ax}^* = \frac{U_{ax}}{1 + \beta\mu} \quad (19)$$

where:  $U_{ax}^*$  is the effective axial velocity,  $U_{ax}$  is the theoretical axial velocity,  $\beta$  is the experimental correction factor, and  $\mu$  is the material loading coefficient.

Similarly, the radial suction speed is also corrected:

$$U_s^* = \frac{U_s}{1 + \gamma\mu} \quad (20)$$

where:  $U_s^*$  is the effective radial velocity,  $U_s$  is the theoretical radial velocity,  $\gamma$  is the experimental correction factor, and  $\mu$  is the material loading coefficient.

In this case, the particle's time in the device is also recalculated:

$$t_{res}^* = \frac{L_{path}}{U_{ax}^*} \quad (21)$$

where:  $t_{res}^*$  is the particle residence time accounting for material loading, and  $L_{path}$  is the particle travel path length.

Similarly, the time to reach the hole is:

$$t_{need}^* = \frac{\Delta r}{U_s^*} \quad (22)$$

where:  $\Delta r$  is the radial distance from the particle trajectory to the central tube.

For the effective implementation of pneumatic classification, the following conditions must be met:

$$t_{res}^* \geq t_{need}^* \quad (23)$$

### Selection of model parameters and coefficients

The parameters and coefficients used in the mathematical model were selected based on the geometric characteristics of the experimental pneumatic screw classifier, the physical properties of wheat flour, and the operating conditions of the fractionation process.

The total airflow rate ( $Q_{tot} = 1.2 \text{ m}^3/\text{s}$ ) was selected according to the fan capacity required to maintain stable pneumatic transport of flour particles inside the classifier. The residual airflow ( $Q_{leak} = 0.05 \text{ m}^3/\text{s}$ ) corresponds to the minimum airflow passing through structural clearances when the adjustable openings are completely closed.

The proportionality coefficient ( $k = 0.35$ ) was determined from the geometry of the adjustable openings and represents the linear relationship between the degree of aperture opening and the airflow entering the perforated central tube. The tangential air velocity ( $u_t = 3 \text{ m/s}$ ) corresponds to the operating conditions of the experimental classifier.

The material loading coefficient ( $\mu$ ) was calculated from the measured mass flow rates of flour and air. This coefficient accounts for the influence of the solid phase on airflow distribution and enables the model to describe two-phase gas–solid flow during pneumatic classification.

The correction coefficients  $\beta$  and  $\gamma$  were adopted as empirical constants following the classical theory of pneumatic conveying and gas–solid particle separation [21, 31, 32]. These coefficients account for the influence of the dispersed solid phase on the effective axial and radial air velocities and compensate for flow deviations arising from particle–air interactions that the simplified analytical model cannot fully capture. Their values were assumed to remain constant under the operating conditions investigated, which is consistent with recent CFD-based

studies on gas–solid flow modeling and pneumatic air classification [31,32].

The aerodynamic drag coefficient ( $C_d = 0.9$ ) was adopted from published data for irregularly shaped flour particles. The suitability of the selected values was supported by the statistical agreement between the calculated and experimental results, as shown in Table 5. The use of empirical correction parameters to represent unresolved gas–solid interactions is consistent with established gas–solid flow and pneumatic air-classifier modeling approaches [21, 31, 32].

### Multi-criteria optimization framework

To determine the optimum operating conditions of the pneumatic screw classifier, the adjustable aperture opening degree ( $\phi$ ) was selected as the principal optimization variable. All other operating parameters, including the airflow rate, classifier geometry, and feed throughput, were maintained constant throughout the analysis.

The objective of the optimization was to identify an operating range that provided a minimum intermediate fraction yield, high normalized protein and starch purity indices, high enrichment and overall selectivity, a favorable relative recovery balance, and maximum or near-maximum fractionation efficiency, while satisfying the pneumatic particle-transport criterion. Accordingly, the favorable operating range was identified using the following criteria:

- minimum intermediate fraction yield;
- high normalized protein purity index in the light fraction;
- high normalized starch purity index in the heavy fraction;
- high protein and starch enrichment selectivities and overall selectivity;
- favorable relative recovery balance;
- maximum or near-maximum fractionation efficiency; and
- fulfillment of the particle-transport criterion,  $t_{res}^* \geq t_{need}^*$ .

The calculated aerodynamic parameters were compared with the experimental separation results over the investigated aperture opening range of  $\phi = 0.10\text{--}0.90$ . On this basis, the range that best balances fraction yield, normalized purity indices, component selectivity, relative recovery, fractionation efficiency, and aerodynamic stability was selected as the multi-criteria operating region.

The combined evaluation identified  $\phi = 0.30\text{--}0.40$  as the favorable operating range. Within this interval, the particle-transport criterion  $t_{res}^* \geq t_{need}^*$  was fulfilled. Although the individual performance indicators reached their maxima at different aperture openings, their best combined balance was maintained across the selected range.

### Performance evaluation criteria

Fractionation performance was evaluated using four complementary groups of indicators: normalized product purity, component yield, enrichment selectivity, and component recovery. To avoid ambiguity, lowercase  $c$  denotes the experimentally measured mass fraction of a component,  $x$  denotes the normalized purity index,  $G$  denotes fraction yield,  $Y$  denotes component yield relative to the initial flour mass, and RRR denotes component recovery. The normalized protein purity index in the light fraction was calculated as:

$$x_{P,L} = \frac{c_{P,L}}{c_{P,L} + c_{S,L}} \cdot 100\% \quad (24)$$

where:  $C_{P,L}$  and  $C_{S,L}$  are the measured protein and starch contents in the light fraction, respectively.

The normalized starch purity index in the heavy fraction was calculated as:

$$x_{S,H} = \frac{c_{S,H}}{c_{S,H} + c_{P,H}} \cdot 100\% \quad (25)$$

where:  $C_{S,H}$  and  $C_{P,H}$  are the measured starch and protein contents in the heavy fraction, respectively.

Equations 24 and 25 express the relative proportions of the two target components – protein and starch – in the corresponding fractions. Therefore,  $x_{P,L}$  and  $x_{S,H}$  are normalized purity indices and should not be interpreted as the directly measured crude protein or starch contents of the fractions.

### Component yield

The protein yield in the light fraction, expressed relative to the initial flour mass, was calculated as:

$$Y_P = \frac{G_L c_{P,L}}{100} \quad (26)$$

where:  $G_L$  is the light-fraction yield (%).

The starch yield in the heavy fraction was calculated as:

$$Y_S = \frac{G_H c_{S,H}}{100} \quad (27)$$

where:  $G_H$  is the heavy-fraction yield (%).

Here,  $Y_P$  and  $Y_S$  represent the amounts of protein and starch recovered in the target fractions per 100 units of initial flour mass.

### Enrichment selectivity

The enrichment coefficients of protein and starch were calculated as:

$$K_{enr,P} = \frac{c_{P,L}}{c_{P,O}}, K_{enr,S} = \frac{c_{S,H}}{c_{S,O}} \quad (28)$$

where:  $C_{P,O}$  and  $C_{S,O}$  are the initial protein and starch contents of the flour, respectively.

The overall enrichment selectivity was defined as the product of the two enrichment coefficients:

$$S_{int} = K_{enr,P} K_{enr,S} \quad (29)$$

This definition is consistent with the experimental calculations: for example,  $2.59 \times 1.47 \approx 3.80$ .

### Component recovery and recovery selectivity

Protein recovery in the light fraction was calculated as:

$$R_P = \frac{Y_P}{c_{P,O}} \cdot 100 = \frac{G_L c_{P,L}}{c_{P,O}} \quad (30)$$

and starch recovery in the heavy fraction was calculated as:

$$R_S = \frac{Y_S}{c_{S,O}} \cdot 100 = \frac{G_H c_{S,H}}{c_{S,O}} \quad (31)$$

where:  $G_L$ ,  $G_H$  and the component contents are entered as numerical percentages,  $R_P$  and  $R_S$  are obtained as percentages.

Recovery selectivity was then defined as:

$$K_S = \frac{R_P}{R_S} \quad (32)$$

A value of  $K_S < 1$  indicates that starch recovery in the heavy fraction predominates over

protein recovery in the light fraction, whereas  $K_s > 1$  indicates a relative predominance of protein recovery. Thus,  $K_s$  characterizes the ratio between the two component recoveries rather than the total amount of recovered material.

The fractionation efficiency ( $E$ , %) was calculated by the following expression:

$$E = \frac{G_L \cdot x_{P,L} + G_H \cdot x_{S,H}}{100} \quad (33)$$

where:  $G_L$  is the yield of the light fraction (%),  $G_H$  is the yield of the heavy fraction (%),  $x_{P,L}$  is the normalized protein purity index in the light fraction, and  $x_{S,H}$  is the normalized starch purity index in the heavy fraction.

## RESULTS AND DISCUSSION

### Engineering calculation of the effect of the adjustable opening degree on the aerodynamic mode of the device

In the pneumatic classifier, the airflow moves through the outer cylinder, and a certain part is sucked in through the holes in the central pipe. As a result of this process, a separation zone is formed inside the device.

In pneumatic classification, the efficiency of particle fractional separation depends directly on the airflow modes within the device, the ratio of axial to radial speeds, and the intensity of air suction through the adjustable holes in the central pipe.

In pneumatic classifier designs, adjustable holes in the central pipe are used to regulate the airflow distribution. Through these holes, part of the airflow is sucked into the interior of the device, resulting in a combination of axial and radial flows inside the device. Such an aerodynamic structure enables the effective use of particles' inertial properties.

When the degree of opening of the adjustable holes in the device changes, the following parameters change: airflow in the ring channel; the amount of air sucked into the central pipe; axial and radial airflow velocities; time of particles in the device; separation efficiency.

In this regard, the main goal of this section is to determine the effect of the degree of adjustability of the device's opening on the geometric parameters and airflow modes through engineering calculations.

As a result of the calculations, the effective operating area of the device, i.e., the «separation window» that ensures constant separation of particles, is determined.

In the calculation of the main geometric and aerodynamic parameters of the pneumatic classifier, the following values were adopted:

### Report initial data (input parameters)

The engineering calculations were performed using the following parameters of the pneumatic screw classifier: outer cylinder diameter  $D = 0.30$  m, central tube diameter  $D_{core} = 0.12$  m, slot length  $L_{sl} = 0.25$  m, screw pitch  $p = 0.10$  m, number of turns  $N = 1$ , total airflow rate  $Q_{tot} = 1.2$  m<sup>3</sup>/s, leakage airflow rate  $Q_{leak} = 0.05$  m<sup>3</sup>/s, tangential velocity  $u_t = 3$  m/s, air density  $\rho_{air} = 1.2$  kg/m<sup>3</sup>, gravitational acceleration  $g = 9.81$  m/s<sup>2</sup>, starch particle density  $\rho_{st} = 1500$  kg/m<sup>3</sup>, average starch particle diameter  $d_{st} = 30$  μm, drag coefficient  $C_d = 0.9$ , and proportionality coefficient  $k = 0.35$ . The aperture opening degree was varied from  $\varphi = 0.00$  to  $0.90$ .

### Determine the geometric parameters of the pneumatic classifier

First, the basic geometric parameters of the apparatus are determined.

Outer cylinder radius:

$$R = \frac{D}{2} = \frac{0.30}{2} = 0.15 \text{ m} \quad (34)$$

Center pipe radius:

$$r_{core} = \frac{D_{core}}{2} = \frac{0.12}{2} = 0.06 \quad (35)$$

Using the geometrical parameters of the classifier and Equations 1–23, the aerodynamic characteristics of the apparatus were calculated for aperture opening degrees ranging from  $\varphi = 0.00$  to  $0.9$ . The calculated values of airflow rates, axial and radial velocities, particle residence times, and separation conditions are summarized in Table 3.

The engineering analysis demonstrated that the degree of aperture opening significantly affects airflow distribution and particle separation in the pneumatic screw classifier. At  $\varphi < 0.188$ , radial suction is insufficient for the effective entrainment of light particles into the central tube. Within  $0.188 \leq \varphi \leq 0.477$ , the conditions for light-particle entrainment and heavy-particle retention

are simultaneously satisfied, defining the effective theoretical separation window. At  $\varphi > 0.477$ , excessive radial airflow progressively entrains larger and denser particles into the central tube, thereby reducing fraction purity and separation selectivity. Accordingly, the calculation points  $\varphi = 0.20, 0.30$  and  $0.40$  correspond to effective separation;  $\varphi = 0.50$  represents a transition condition slightly above the theoretical upper limit; and  $\varphi = 0.60\text{--}0.90$  corresponds to deteriorated separation conditions caused by excessive particle entrainment.

The following expression determines the degree of opening of the hole:

$$\varphi = \frac{A_{open}}{A_{max}} \quad (36)$$

where:  $A_{open}$  is the effective open area of the slots, and  $A_{max}$  is the maximum slot opening area.

Based on the aerodynamic calculations, the effective operating range of the classifier was determined as:

$$0.188 \leq \varphi \leq 0.477 \quad (37)$$

This range corresponds to the effective separation zone, where light particles are entrained into the central tube while heavy particles remain in the lower fraction. At  $\varphi < 0.188$ , radial suction is insufficient for complete separation, whereas at  $\varphi > 0.477$ , excessive suction causes partial entrainment of heavy particles, reducing heavy-fraction purity.

## Experimental verification of the mathematical model

To verify the adequacy of the proposed mathematical model, theoretical calculations were compared with experimental data obtained from a pneumatic screw classifier operating at a throughput of 150 kg/h.

According to the calculations, the effective separation region (“separation window”) lies within  $0.188 \leq \varphi \leq 0.477$ , where the conditions for light-particle entrainment and heavy-particle retention are simultaneously satisfied. Experimental analysis showed that the individual performance indicators reached their maximum values at different degrees of aperture opening. The highest normalized protein purity index and maximum overall selectivity were obtained at  $\varphi = 0.30$ , with  $x_{P,L} = 93.99\%$  and  $S_{int} = 3.959$ , respectively. The maximum fractionation efficiency was achieved at  $\varphi = 0.40$  ( $E = 78.92\%$ ), where the intermediate fraction yield also reached its minimum value of 17.19%.

Despite individual maxima occurring at different operating points, the aperture opening range of  $\varphi = 0.30\text{--}0.40$  provided the best overall balance of minimum intermediate fraction yield, high normalized protein and starch purity indices, high enrichment selectivity, favorable recovery balance, and near-maximum fractionation efficiency. The experimentally selected multi-criteria operating range lies entirely within the theoretically predicted separation window.

**Table 3.** Calculated aerodynamic parameters at different aperture opening degrees for a classifier throughput of 150 kg/h

| $\varphi$ | $Q_{core}, m^3/s$ | $Q_{ann}, m^3/s$ | $U_{ax}, m/s$ | $U_s, m/s$ | $U'_{ax}, m/s$ | $U'^*_s, m/s$ | $t'_{res}, s$ | $t'_{need}, s$ | Condition                                                                                            |
|-----------|-------------------|------------------|---------------|------------|----------------|---------------|---------------|----------------|------------------------------------------------------------------------------------------------------|
| 0.0       | 0.050             | 1.150            | 19.368        | 0.530      | 18.823         | 0.515         | 0.035         | 0.087          | Residence-time criterion not fulfilled                                                               |
| 0.1       | 0.085             | 1.115            | 18.778        | 0.901      | 18.250         | 0.876         | 0.036         | 0.051          |                                                                                                      |
| 0.2       | 0.120             | 1.080            | 18.189        | 1.273      | 17.677         | 1.237         | 0.037         | 0.036          | Effective separation criteria fulfilled                                                              |
| 0.3       | 0.155             | 1.045            | 17.599        | 1.644      | 17.104         | 1.598         | 0.039         | 0.028          |                                                                                                      |
| 0.4       | 0.190             | 1.010            | 17.010        | 2.015      | 16.531         | 1.959         | 0.040         | 0.022          |                                                                                                      |
| 0.5       | 0.225             | 0.975            | 16.420        | 2.387      | 15.958         | 2.320         | 0.041         | 0.019          | Residence-time criterion fulfilled; upper theoretical separation limit exceeded (transition region)  |
| 0.6       | 0.260             | 0.940            | 15.831        | 2.758      | 15.386         | 2.681         | 0.043         | 0.016          | Residence-time criterion fulfilled; separation quality compromised by excessive particle entrainment |
| 0.7       | 0.295             | 0.905            | 15.241        | 3.130      | 14.813         | 3.042         | 0.045         | 0.014          |                                                                                                      |
| 0.8       | 0.330             | 0.870            | 14.652        | 3.501      | 14.240         | 3.402         | 0.046         | 0.013          |                                                                                                      |
| 0.9       | 0.365             | 0.835            | 14.062        | 3.872      | 13.667         | 3.763         | 0.048         | 0.011          |                                                                                                      |

The comparison presented in Table 4 shows that the theoretically predicted separation window,  $0.188 \leq \varphi \leq 0.477$ , encompasses the experimentally selected favorable operating range,  $\varphi = 0.30\text{--}0.40$ . At  $\varphi = 0.30$ , the classifier exhibited the maximum overall selectivity ( $S_{\text{int}} = 3.959$ ) and the highest normalized protein purity index ( $x_{\text{PL}} = 93.99\%$ ), while maintaining a low intermediate fraction yield of 17.57% and a fractionation efficiency of 78.49%. At  $\varphi = 0.40$ , the intermediate fraction yield decreased further to 17.19%, and the maximum fractionation efficiency of 78.92% was achieved, together with a normalized starch purity index of 96.52% and an overall selectivity of 3.946. Thus, the two adjacent aperture opening conditions provide complementary technological advantages. Accordingly, the range of  $\varphi = 0.30\text{--}0.40$  was selected as the most favorable multi-criteria operating region rather than identifying the optimum solely from the extreme value of a single performance indicator.

To further assess the agreement between the calculated and experimental results, a quantitative statistical verification was performed at identical aperture opening degrees ( $\varphi = 0.10\text{--}0.90$ ). Model performance was evaluated using the mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination ( $R^2$ ). The results are summarized in Table 5.

The calculated and experimental results demonstrated close agreement for all investigated indicators. The coefficients of determination ranged from 0.998 to 1.000. The highest relative errors were observed for the intermediate and light fraction yields, with MAPE values of 4.56% and 4.47%, respectively. The MAPE was 1.22% for the heavy-fraction yield and 1.29% for the fractionation efficiency. The normalized protein purity index and protein enrichment selectivity were predicted with a MAPE of 0.04%. In contrast, the normalized starch purity index, starch enrichment selectivity, and overall selectivity exhibited MAPE values of 0.14%.

Overall, the statistical verification confirms that the proposed mathematical model adequately represents the principal relationships between the degree of aperture opening and the aerodynamic fractionation indicators over the investigated operating range. Therefore, the model can be used for engineering calculations, operating-condition selection, and process optimization of pneumatic screw classifiers.

### Variation of fraction yields depending on the aperture opening degree

The influence of the aperture opening degree ( $\varphi$ ) on the yields of the light, intermediate, and

**Table 4.** Comparison of theoretical predictions and experimental observations

| Criterion/parameter                                                    | Theoretical prediction                               | Experimental observation                                                          | Interpretation                                                                                                                             |
|------------------------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Effective operating (separation) range                                 | $0.188 \leq \varphi \leq 0.477$                      | $\varphi = 0.30\text{--}0.40$                                                     | The experimentally selected operating range lies within the theoretically predicted separation window.                                     |
| Minimum intermediate fraction yield                                    | —                                                    | 17.19–17.57% at $\varphi = 0.30\text{--}0.40$                                     | Indicates reduced particle accumulation in the transition fraction and more complete classification                                        |
| Maximum fractionation efficiency, $E$                                  | —                                                    | 78.92% at $\varphi = 0.40$                                                        | Highest experimentally observed process efficiency                                                                                         |
| Maximum overall selectivity, $S_{\text{int}}$                          | —                                                    | 3.959 at $\varphi = 0.30$                                                         | Highest combined protein–starch enrichment selectivity                                                                                     |
| Selected multi-criteria operating range                                | Within the theoretically predicted separation window | $\varphi = 0.30\text{--}0.40$                                                     | Best combined balance of fraction yield, normalized purity indices, enrichment selectivity, recovery balance, and fractionation efficiency |
| Normalized protein purity index in the light fraction, $x_{\text{PL}}$ | —                                                    | 93.01–93.99% at $\varphi = 0.30\text{--}0.40$                                     | High normalized protein purity within the selected operating range                                                                         |
| Normalized starch purity index in the heavy fraction, $x_{\text{SH}}$  | —                                                    | 95.83–96.52% at $\varphi = 0.30\text{--}0.40$                                     | High normalized starch purity within the selected operating range                                                                          |
| Deterioration of separation at large aperture openings                 | $\varphi > 0.477$                                    | Observed from $\varphi \geq 0.50$ and pronounced at $\varphi = 0.60\text{--}0.90$ | Excessive particle entrainment and re-mixing reduce separation quality                                                                     |

heavy fractions and on protein–starch separation performance was investigated.

Figure 3 illustrates the effect of the aperture opening degree ( $\phi$ ) on the yields of the light ( $G_L$ ), intermediate ( $G_M$ ), and heavy ( $G_H$ ) fractions obtained during the pneumatic fractionation of wheat flour. A pronounced redistribution of material among the three fractions was observed as the aperture opening increased from 0.10 to 0.90.

At low aperture opening degrees ( $\phi = 0.10$ – $0.20$ ), the heavy fraction accounted for approximately 59.31–57.12% of the total feed, whereas the light fraction yield was 6.27–16.77%. Under these conditions, the restricted airflow entering the central tube generated insufficient aerodynamic drag to entrain a significant number of fine, protein-rich particles into the light fraction. Consequently, the majority of particles followed the outer helical trajectory and were discharged into the heavy fraction.

As the aperture opening increased to  $\phi = 0.30$ – $0.40$ , the light fraction yield increased sharply to 27.30–28.71%, while the intermediate fraction reached its minimum values of 17.57–17.19%. This behavior indicates that the airflow distribution became favorable for efficient particle separation, directing most transitional particles toward either the light or heavy fraction rather than remaining insufficiently separated in the intermediate fraction. The reduction in the intermediate fraction yield is generally considered an indicator of improved classification efficiency because fewer particles remain in the transition zone between the two principal separation pathways.

Further increasing the aperture opening beyond  $\phi = 0.50$  caused a continuous increase in the light-fraction yield, reaching 48.25% at  $\phi = 0.90$ , while the heavy fraction decreased to 17.75%. Although a larger aperture enhances

particle entrainment into the central tube, excessive airflow also transports an increasing number of coarse starch-rich particles into the light fraction. As a result, the increase in light-fraction yield is accompanied by a deterioration in fraction purity and overall separation performance, as discussed in the subsequent sections.

The observed trends are fully consistent with the proposed aerodynamic model, which predicts that increasing the aperture opening increases the airflow entering the perforated central tube, thereby increasing the aerodynamic drag acting on flour particles. When the drag force exceeds the combined effects of gravity and centrifugal force, progressively larger particles are transported into the central collection zone. Similar relationships between airflow intensity, particle entrainment, and classification efficiency have been reported for pneumatic classifiers and gas–solid separation systems in previous studies [14, 21, 24, 30, 32].

These findings demonstrate that the aperture opening degree is the dominant operating parameter governing particle distribution among the three fractions. Although the light-fraction yield continues to increase across the investigated range, the most favorable operating region is observed near  $\phi = 0.30$ – $0.40$ , where efficient separation is achieved while maintaining a minimal intermediate fraction and high product quality.

The observed redistribution of material is consistent with the aerodynamic mechanism incorporated into the proposed mathematical model. According to the model, increasing the aperture opening increases the airflow entering the perforated central tube, thereby increasing the aerodynamic drag force acting on flour particles. As the drag force progressively exceeds the combined effects of gravity and centrifugal force, particles with progressively larger equivalent

**Table 5.** Statistical verification of the proposed mathematical model

| Indicator                                      | n | MAE   | RMSE  | MAPE (%) | R <sup>2</sup> |
|------------------------------------------------|---|-------|-------|----------|----------------|
| Light fraction yield ( $G_L$ )                 | 9 | 1.290 | 1.370 | 4.47     | 1.0000         |
| Intermediate fraction yield ( $G_M$ )          | 9 | 1.193 | 1.237 | 4.56     | 1.0000         |
| Heavy fraction yield ( $G_H$ )                 | 9 | 0.547 | 0.650 | 1.22     | 0.9981         |
| Normalized protein purity index ( $x_{PL}$ )   | 9 | 0.037 | 0.077 | 0.04     | 1.0000         |
| Normalized starch purity index ( $x_{SH}$ )    | 9 | 0.138 | 0.143 | 0.14     | 0.9986         |
| Fractionation efficiency ( $E$ )               | 9 | 0.796 | 0.864 | 1.29     | 0.9993         |
| Protein enrichment selectivity ( $K_{enr,P}$ ) | 9 | 0.001 | 0.002 | 0.04     | 1.0000         |
| Starch enrichment selectivity ( $K_{enr,S}$ )  | 9 | 0.002 | 0.002 | 0.14     | 0.9986         |
| Overall selectivity ( $S_{int}$ )              | 9 | 0.005 | 0.005 | 0.14     | 1.0000         |

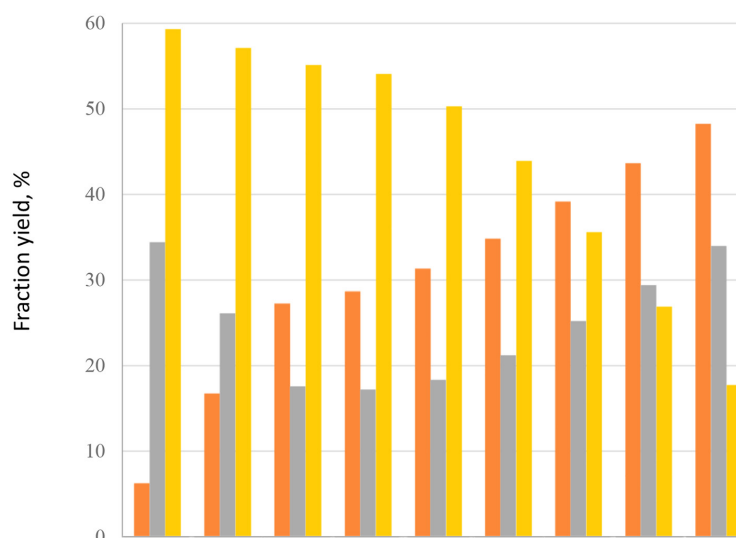


**Figure 3.** Variation of light, intermediate, and heavy fraction yields depending on the aperture opening degree

diameters are entrained into the central collection zone. Consequently, the probability of transferring particles from the heavy fraction to the light fraction increases continuously with  $\phi$ , explaining the experimentally observed increase in  $G_L$  and corresponding decrease in  $G_H$ .

An important feature of Figure 3 is the presence of an optimal operating region rather than a single optimal value. Although the light fraction yield continues to increase over the entire investigated range, the objective of pneumatic fractionation is not to maximize the quantity of the light fraction alone, but to achieve efficient separation between protein-rich and starch-rich particles. Therefore, the operating region at  $\phi = 0.30$ – $0.40$  represents the best compromise between particle entrainment and particle discrimination, where the intermediate fraction reaches its minimum value. In contrast, the light and heavy fractions remain effectively differentiated. This observation is fully consistent with the optimization criterion and confirms the validity of the selected operating conditions.

The present results also demonstrate that fraction yield alone cannot be considered a sufficient indicator of classifier performance. An increase in the light fraction yield does not necessarily correspond to improved separation because excessive airflow promotes the entrainment of coarse starch-rich particles together with fine protein-rich particles. Consequently, product purity and selectivity may decrease despite higher material recovery. This phenomenon explains why the maximum light-fraction yield observed at high

aperture-opening degrees does not coincide with the highest separation efficiency reported later in Figures 4 and 5.

The theoretical predictions of the proposed model fully support the experimentally observed trends. They are consistent with previous investigations on pneumatic classification and gas–solid particle separation, which likewise reported that airflow intensity is the dominant factor governing particle entrainment, classification efficiency, and separation selectivity [10, 14, 21, 24, 30, 32]. The close agreement between the theoretical model, the experimental results, and the statistical verification presented in Table 5 further confirms that the proposed mathematical model adequately describes the behavior of the pneumatic screw classifier over the investigated operating range.

Overall, Figure 3 demonstrates that the aperture opening degree is the primary control parameter governing the redistribution of particles among the three fractions. While increasing  $\phi$  promotes the transfer of particles toward the light fraction, the optimal operating region is achieved at  $\phi \approx 0.30$ – $0.40$ , where efficient particle classification is achieved before excessive particle entrainment begins to reduce separation quality.

### Variation of normalized purity indices and fractionation efficiency depending on the aperture opening degree

Figure 4 presents the effect of the aperture opening degree ( $\phi$ ) on the normalized protein purity index in the light fraction ( $x_{P,L}$ ), the normalized

starch purity index in the heavy fraction ( $x_{s,H}$ ), and the overall fractionation efficiency ( $E$ ). These parameters characterize the quality and effectiveness of component separation achieved during the pneumatic fractionation process.

As the aperture opening increased from  $\phi = 0.10$  to  $\phi = 0.20$ , the normalized protein purity index in the light fraction increased from 90.21% to 92.09%, indicating more efficient entrainment of fine protein-rich particles into the central collection tube. The normalized protein purity index subsequently reached its maximum of 93.99% at  $\phi = 0.30$ , then gradually decreased to 47.00% at  $\phi = 0.90$ . In contrast, the normalized starch purity index in the heavy fraction remained consistently high throughout the investigated operating range, increasing slightly from 95.08% to 97.67%. The fractionation efficiency exhibited a pronounced maximum, increasing from 62.04% at  $\phi = 0.10$  to 78.92% at  $\phi = 0.40$ , then gradually declining to 40.01% at  $\phi = 0.90$ .

The different behavior of the normalized protein and starch purity indices reflects the distinct aerodynamic characteristics of flour particles. Protein-rich particles are generally finer, lighter, and exhibit lower terminal settling velocities than starch-rich particles. Consequently, they are more sensitive to variations in airflow intensity and are preferentially entrained into the central tube under moderate aerodynamic conditions. However, excessive airflow through larger aperture openings gradually entrains an increasing number of coarse, starch-rich particles along with fine,

protein-rich particles, thereby reducing the normalized protein purity index of the light fraction. This behavior explains the continuous decline in  $x_{P,L}$  observed beyond  $\phi \approx 0.30$ – $0.40$ .

Unlike the normalized protein purity index, the normalized starch purity index in the heavy fraction remained remarkably stable because coarse starch granules possess larger equivalent diameters, higher particle density, and greater inertial resistance to aerodynamic entrainment. Even when the airflow intensity increased, most starch-rich particles continued to follow the outer spiral trajectory and accumulated in the heavy fraction. Consequently, only minor variations in the normalized starch purity index were observed over the investigated operating range. This result indicates that the heavy fraction is considerably less sensitive to airflow redistribution than the light fraction.

The behavior of the fractionation efficiency closely follows the combined evolution of the normalized protein and starch purity indices. The highest efficiency was achieved within the aperture opening range  $\phi = 0.30$ – $0.40$ , where both normalized purity indices remained high, while the intermediate fraction reached its minimum (Figure 3). At lower aperture openings, insufficient airflow limited the selective transport of fine particles into the light fraction. In contrast, at higher aperture openings, excessive entrainment led to partial mixing of starch- and protein-rich particles. Consequently, the separation efficiency decreased despite the increasing yield of the light fraction.

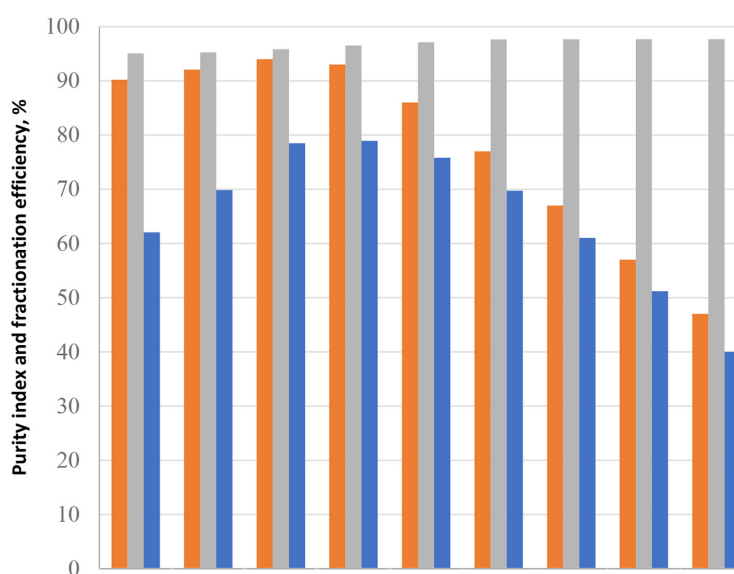


**Figure 4.** Variation of the normalized protein purity index, normalized starch purity index, and fractionation efficiency depending on the aperture opening degree

These experimental observations are fully consistent with the proposed mathematical model. According to the model, the aperture opening regulates the airflow entering the perforated central tube. It therefore controls the balance between aerodynamic drag, gravitational force, centrifugal force, and particle residence time. Within the optimum operating region ( $\phi \approx 0.30$ – $0.40$ ), these forces remain balanced, allowing efficient discrimination between particles with different aerodynamic properties. At larger aperture openings, the drag force increasingly dominates the particle motion, reducing the selectivity of the separation process because particles with progressively larger equivalent diameters are entrained into the light fraction.

The results presented in Figure 4 also complement the findings obtained for the fraction yields (Figure 3). Although the light-fraction yield increased with increasing aperture opening, its normalized protein purity index decreased beyond the optimum operating region. This demonstrates that maximizing fraction yield alone cannot be regarded as an appropriate optimization criterion, since higher recovery may be accompanied by deterioration of product quality. Therefore, fraction yield and normalized purity indices must be evaluated simultaneously to identify the true optimum operating conditions.

The observed relationships agree with previous studies showing that effective air classification requires sufficient aerodynamic drag to entrain fine particles while remaining below the level at which coarse particles are increasingly transferred into the light fraction [10, 14, 19, 21, 30, 32]. The excellent agreement among the experimental observations, theoretical predictions, and statistical verification presented in Table 5 further confirms the adequacy of the proposed mathematical model for predicting the purification performance of the pneumatic screw classifier.

Overall, Figure 4 demonstrates that the optimum operating region of the pneumatic screw classifier is determined not by the maximum fraction yield but by the simultaneous achievement of high normalized purity indices and maximum fractionation efficiency. These findings provide the physical basis for interpreting the selectivity coefficients discussed in Figure 5, where both enrichment and recovery characteristics are analyzed in greater detail.

## Effect of the aperture opening degree on protein and starch selectivity indices

Figure 5 illustrates the effect of the aperture opening degree ( $\phi$ ) on the principal selectivity indicators of the pneumatic fractionation process: protein enrichment selectivity ( $K_{\text{enr,p}}$ ), starch enrichment selectivity ( $K_{\text{enr,s}}$ ), overall selectivity ( $S_{\text{int}}$ ), and recovery selectivity ( $K_s$ ). The enrichment coefficients characterize changes in the concentrations of the target components relative to their initial contents in the feed flour. The overall selectivity combines protein and starch enrichment into a single indicator of separation performance. In contrast,  $K_s$  represents the relative recovery of protein in the light fraction compared with starch recovery in the heavy fraction. Therefore, these indicators should be interpreted jointly rather than as independent optimization criteria.

### Protein enrichment selectivity ( $K_{\text{enr,p}}$ )

The protein enrichment selectivity increased from 2.578 at  $\phi = 0.10$  to its maximum value of 2.686 at  $\phi = 0.30$ . At  $\phi = 0.40$ , it remained close to the maximum of 2.657, then gradually decreased to 1.343 at  $\phi = 0.90$ . The initial increase indicates that opening the adjustable slots improved the selective entrainment of fine protein-rich particles into the central collection tube.

The maximum observed at  $\phi = 0.30$  reflects a favorable balance between radial airflow intensity and particle discrimination. Under these conditions, the aerodynamic drag was sufficient to transport fine protein-rich particles toward the light fraction. In contrast, most coarse starch-rich particles remained in the outer helical flow under the combined effects of gravitational, centrifugal, and inertial forces.

When the aperture opening exceeded  $\phi = 0.40$ , the increasing radial airflow progressively entrained larger starch-rich particles together with the fine protein-rich particles. Consequently, the light-fraction yield continued to increase, but its compositional selectivity deteriorated. This explains the continuous decline in  $K_{\text{enr,p}}$  from 2.457 at  $\phi = 0.50$  to 1.343 at  $\phi = 0.90$ .

The values obtained at  $\phi = 0.30$ – $0.40$  demonstrate that high protein enrichment was maintained, alongside the minimum intermediate fraction yield observed in Figure 3 and the high normalized protein purity and fractionation efficiency shown in Figure 4. Thus, the maximum

$K_{\text{enr,P}}$  at  $\varphi = 0.30$  supports selecting  $\varphi = 0.30\text{--}0.40$  as the favorable multi-criteria operating range.

### Starch enrichment selectivity ( $K_{\text{enr,S}}$ )

The starch enrichment selectivity exhibited considerably smaller variations than the protein enrichment selectivity. The coefficient increased gradually from 1.463 at  $\varphi = 0.10$  to approximately 1.503 at  $\varphi = 0.80\text{--}0.90$ . Within the selected operating range of  $\varphi = 0.30\text{--}0.40$ ,  $K_{\text{enr,S}}$  ranged from 1.474 to 1.485.

The relative stability of  $K_{\text{enr,S}}$  is associated with the physical and aerodynamic properties of starch-rich particles. Owing to their larger equivalent diameter, higher density, and greater inertia, these particles are less sensitive to moderate changes in radial airflow and tend to remain in the outer separation zone and accumulate in the heavy fraction.

The slight increase in  $K_{\text{enr,S}}$  with aperture opening indicates that the heavy fraction remained consistently enriched in starch throughout the investigated operating range. However, the absence of a pronounced maximum also shows that starch enrichment selectivity alone cannot identify the optimum operating condition. The deterioration observed at large-aperture openings primarily resulted from contamination of the light fraction by starch-rich particles rather than from a substantial loss of starch enrichment in the heavy fraction.

These observations are consistent with previous air-classification studies showing that coarse and dense starch-rich particles have greater resistance to aerodynamic entrainment than fine protein-rich particles [10, 14, 17, 19, 30].

### Overall selectivity ( $S_{\text{int}}$ )

The overall selectivity increased from 3.770 at  $\varphi = 0.10$  to 3.856 at  $\varphi = 0.20$ , reaching a maximum of 3.959 at  $\varphi = 0.30$ . At  $\varphi = 0.40$ , the coefficient remained close to the maximum at 3.946. Further enlargement of the aperture opening caused a continuous decrease in  $S_{\text{int}}$ , reaching 2.018 at  $\varphi = 0.90$ .

Because  $S_{\text{int}}$  is calculated from the combined protein and starch enrichment coefficients, its variation reflects the overall compositional contrast between the light and heavy fractions. The starch enrichment coefficient remained comparatively stable, whereas protein enrichment declined sharply at large aperture openings. Therefore, the reduction in  $S_{\text{int}}$  beyond  $\varphi = 0.30\text{--}0.40$  was governed mainly by the progressive contamination of the light protein-rich fraction with coarse starch-rich particles.

The maximum  $S_{\text{int}} = 3.959$  at  $\varphi = 0.30$ , together with the near-maximum value of 3.946 at  $\varphi = 0.40$ , confirms that the strongest combined protein–starch separation was achieved within this interval. The minimum intermediate-fraction yield and the maximum or near-maximum fractionation efficiency characterized the same operating range. Consequently, the overall selectivity results support the multi-criteria optimum for  $\varphi = 0.30\text{--}0.40$ .

The observed decrease in  $S_{\text{int}}$  at larger aperture openings is consistent with the proposed mathematical model. As the radial airflow becomes excessive, aerodynamic drag increasingly exceeds the particle-discrimination threshold, and particles with different sizes and compositions begin

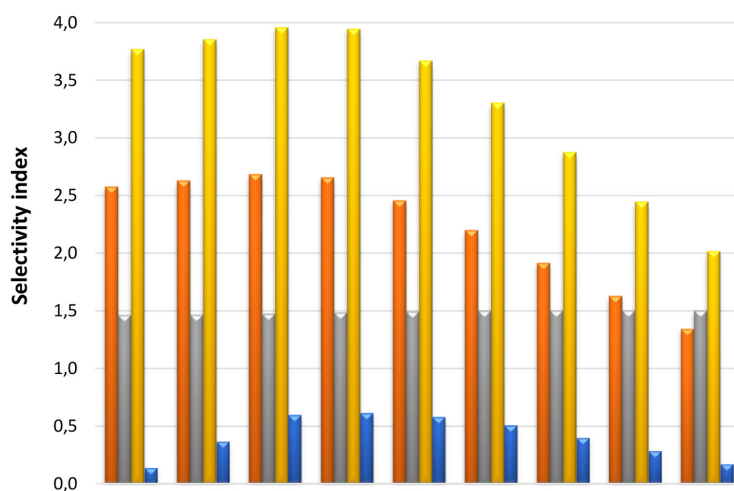


**Figure 5.** Variation of protein and starch selectivity indices depending on the aperture opening degree

to follow similar trajectories. This promotes partial re-mixing and reduces the compositional difference between the separated fractions [10, 14, 21, 24, 30–32].

### Recovery selectivity ( $K_s$ )

The recovery selectivity coefficient is defined as the ratio of protein recovery in the light fraction to starch recovery in the heavy fraction:  $K_s = \frac{R_p}{R_s}$ .

Accordingly,  $K_s$  characterizes the relative recovery balance between the two target components rather than the total quantity of material recovered. A value of  $K_s < 1$  indicates that starch recovery in the heavy fraction exceeds protein recovery in the light fraction, whereas  $K_s > 1$  would indicate the predominance of protein recovery.

The experimental  $K_s$  values were 0.140, 0.369, 0.596, 0.613, 0.579, 0.506, 0.401, 0.288, and 0.173 for aperture opening degrees from  $\phi = 0.10$  to  $0.90$ , respectively. Thus,  $K_s$  increased from 0.140 at  $\phi = 0.10$  to its maximum value of 0.613 at  $\phi = 0.40$ , after which it gradually decreased to 0.173 at  $\phi = 0.90$ .

The initial increase in  $K_s$  indicates that enlarging the aperture to  $\phi = 0.40$  progressively improved protein recovery relative to starch recovery. At low aperture sizes, insufficient radial airflow limited the transfer of fine, protein-rich particles into the light fraction. At the same time, a large proportion of the material remained in the heavy and intermediate fractions. Increasing the aperture opening improved the entrainment of protein-rich particles and shifted the relative recovery balance toward protein.

The maximum  $K_s = 0.613$  at  $\phi = 0.40$  represents the closest recovery balance observed between protein and starch. Nevertheless,  $K_s$  remained below unity at all investigated operating points, indicating that starch recovery in the heavy fraction was consistently greater than protein recovery in the light fraction.

Beyond  $\phi = 0.40$ , the progressive decrease in  $K_s$  shows that the continued increase in light-fraction yield did not produce a corresponding improvement in relative protein recovery. Instead, the stronger airflow promoted increasingly non-selective particle transport, including the entrainment of coarse starch-rich particles into the light fraction. Consequently, the additional material transferred toward the light fraction contributed more to fraction contamination than to selective protein recovery.

This interpretation is supported by the simultaneous decreases in normalized protein purity, protein enrichment selectivity, overall selectivity, and fractionation efficiency at large aperture openings. Therefore, a higher light-fraction yield cannot be regarded as evidence of improved protein recovery or better separation quality.

The recovery-selectivity curve indicates that the most favorable balance between relative component recovery and separation quality occurred near  $\phi = 0.30$ – $0.40$ . Within this interval,  $K_s$  remained close to its maximum value, while protein enrichment, overall selectivity, normalized purity indices, and fractionation efficiency were also high. Consequently,  $K_s$  should be evaluated together with fraction yields, normalized purity indices, enrichment selectivities, and fractionation efficiency rather than being used as an independent optimization criterion.

### Overall interpretation of Figure 5

The combined behavior of the four selectivity indicators confirms the existence of a favorable operating region rather than a single universally optimal aperture opening. At  $\phi = 0.30$ , the maximum protein enrichment selectivity and overall selectivity were obtained. At  $\phi = 0.40$ , recovery selectivity reached its maximum, while fractionation efficiency was also highest and the intermediate fraction yield was lowest.

Therefore, the aperture opening range of  $\phi = 0.30$ – $0.40$  provides the best combined balance among component enrichment, overall separation selectivity, relative recovery, fraction redistribution, and fractionation efficiency. At smaller openings, insufficient radial airflow limits protein-rich particle entrainment, whereas at larger openings excessive aerodynamic drag reduces particle discrimination and promotes non-selective re-mixing. These results are consistent with the aerodynamic mechanism described by the proposed mathematical model and support the selected multi-criteria operating range.

### Integrated remarks of the results

The combined results presented in Figures 3–5 demonstrate that the performance of the pneumatic screw classifier cannot be evaluated using a single technological indicator. Fraction yield characterizes the redistribution of material, the normalized purity indices describe the

compositional quality of the separated fractions, and the selectivity and recovery coefficients reflect component enrichment and recovery balance. Therefore, the favorable operating condition was identified through a multi-criteria evaluation of these complementary indicators.

The experimentally observed behavior is consistent with the aerodynamic mechanisms incorporated into the proposed mathematical model. At small-aperture openings, insufficient radial airflow limits the entrainment of fine, protein-rich particles into the central tube. It causes a considerable proportion of the material to remain in the intermediate and heavy fractions. At large aperture openings, excessive aerodynamic drag progressively entrains coarser starch-rich particles into the light fraction, thereby reducing particle discrimination, normalized protein purity, enrichment selectivity, and fractionation efficiency. Within  $\phi = 0.30\text{--}0.40$ , the competing effects of aerodynamic drag, gravitational settling, centrifugal force, particle inertia, and residence time remain comparatively balanced.

The theoretically predicted separation window,  $0.188 \leq \phi \leq 0.477$ , encompasses the experimentally selected favorable operating range,  $\phi = 0.30\text{--}0.40$ . The quantitative statistical verification also demonstrated close agreement between the calculated and experimental results, with coefficients of determination ranging from 0.998 to 1.000 and MAPE values not exceeding 4.56%. These findings confirm that the proposed model adequately represents the principal relationships governing airflow distribution and particle separation over the investigated operating range.

Overall, the selected range of  $\phi = 0.30\text{--}0.40$  represents the most technologically justified operating region because it provides the best combined balance of fraction redistribution, normalized product purity, component selectivity, relative recovery, and fractionation efficiency. The agreement among theoretical calculations, experimental observations, and statistical verification supports the use of the proposed model for engineering analysis and for selecting operating conditions in pneumatic screw classifiers.

### Limitations and applicability of the model

The proposed mathematical model was developed to describe the main aerodynamic mechanisms governing dry fractionation in a pneumatic screw classifier. Therefore, the model focuses on

macroscopic airflow behavior and particle separation phenomena. Individual particle collisions, agglomeration effects, particle shape variability, and local turbulent vortex structures were not explicitly considered.

This simplification is considered appropriate for the operating conditions investigated, which were characterized by a relatively low material loading coefficient,  $\mu \approx 0.029$ . Under these conditions, particle separation is governed primarily by the interaction among axial, radial, and tangential airflow components, aerodynamic drag, gravitational settling, centrifugal force, particle inertia, and residence time. The objective of the study was not to develop a detailed CFD model but to establish a compact engineering model suitable for process analysis and operating-condition selection.

The experiments were performed using recombined fractions that were thoroughly homogenized before subsequent runs. At the same time, fresh flour from the same initial batch was added only to compensate for documented losses from sampling, collection, and handling. Nevertheless, minor cumulative changes in particle-size distribution or moisture content resulting from repeated material circulation could not be completely excluded, as these effects were not evaluated separately. Future investigations using independent fresh-flour batches at each operating condition would allow this potential influence to be quantified.

The model can be applied to engineering calculations, process optimization, and the preliminary design of pneumatic classifiers for the dry fractionation of wheat flour and other dispersed plant materials with similar physical properties. For systems operating at substantially higher capacities or with significantly higher solid-phase concentrations, additional parameter calibration and experimental verification may be required.

### CONCLUSIONS

The present study developed and experimentally verified a mathematical model describing aerodynamic particle separation during the dry fractionation of wheat flour in a pneumatic screw classifier. The proposed model accounts for the distribution of axial, radial, and tangential airflow components, the degree of aperture opening, material loading, aerodynamic drag, gravitational and centrifugal forces, and particle residence-time conditions. Engineering calculations were performed

for a classifier throughput of 150 kg/h and a material loading coefficient of approximately  $\mu = 0.029$ .

The theoretical analysis identified an effective separation window of  $0.188 \leq \varphi \leq 0.477$ . The experimentally selected operating range of  $\varphi = 0.30\text{--}0.40$  lies entirely within this window. Within the selected range, the intermediate fraction yield was minimized to 17.19–17.57%, while the normalized protein purity index in the light fraction remained within 93.01–93.99%, the normalized starch purity index in the heavy fraction within 95.83–96.52%, overall selectivity within 3.946–3.959, and fractionation efficiency within 78.49–78.92%.

The individual performance indicators reached their highest values at different aperture openings. At  $\varphi = 0.30$ , the maximum overall selectivity of 3.959 and the highest normalized protein purity index of 93.99% were obtained. At  $\varphi = 0.40$ , the intermediate fraction yield reached its minimum value of 17.19%, and the maximum fractionation efficiency of 78.92% was achieved. Therefore, the selected operating range represents the best combined balance among fraction redistribution, normalized product purity, enrichment selectivity, recovery balance, and fractionation efficiency rather than the maximum of a single criterion.

Quantitative statistical comparison demonstrated close agreement between the calculated and experimental results. The coefficients of determination ranged from 0.998 to 1.000, and the maximum mean absolute percentage error was 4.56%. These results confirm that the proposed engineering model adequately describes the principal relationships governing airflow distribution and particle separation over the investigated operating range.

The developed model can be used as a practical engineering tool for evaluating classifier operating conditions, optimizing aperture opening and material loading, and supporting the preliminary design and scale-up of pneumatic screw classifiers. The proposed approach contributes to the development of energy-efficient, water-free, and environmentally sustainable dry fractionation technologies to produce protein- and starch-enriched wheat flour fractions.

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