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DETERMINATION OF THE OPTIMAL AIRFLOW VELOCITY FOR FLOUR SEPARATION FROM BRAN MIXTURES BY PNEUMATIC SEPARATION

Karabaev Dilshod[1].

[1] Doctor of science (Dsc), Professor, Tashkent Chemical Technology Institute.

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Key words: *pneumatic separation, airflow velocity, flour recovery, bran–flour mixture, particle classification, separation efficiency, pneumatic separator, flour-milling technology.*

ABSTRACT
This study aimed to determine the optimal airflow velocity for recovering flour particles from bran–flour mixtures using pneumatic separation. A laboratory-scale pneumatic separator equipped with an air compressor, receiver, regulating valve, rotameter, separation chamber, and fraction collection system was designed and tested. Experiments were conducted using 100 g samples of bran–flour mixture obtained from the final stage of industrial flour milling, with airflow velocities ranging from 0.56 to 0.70 m/s. The results showed that flour recovery efficiency strongly depends on airflow velocity. At 0.56 m/s, fine-particle entrainment was incomplete, whereas excessive velocities above 0.65 m/s reduced separation selectivity due to turbulence and coarse-particle carryover. The highest efficiency was achieved at 0.62 m/s, where flour recovery reached approximately 73%. The findings confirm that optimized airflow velocity improves separation efficiency, reduces mechanical loading on sieving surfaces, and enhances the technological performance of pneumatic flour classification systems.

PNEVMATIK SEPARATSIYA USULI ORQALI KEPAK ARALASHMALARIDAN UNNI AJRATISH UCHUN OPTIMAL HAVO OQIMI TEZLIGINI ANIQLASH

Kalit so'zlar: *pnevmatik separatsiya, havo oqimi tezligi, unni ajratib olish, kepak–un aralashmasi, zarrachalarni klassifikatsiyalash, separatsiya samaradorligi, pnevmatik separator, un tortish texnologiyasi.*

ANNOTATSIYA
Ushbu tadqiqotning maqsadi pnevmatik separatsiya usuli orqali kepak–un aralashmalaridan un zarrachalarini ajratib olish uchun optimal havo oqimi tezligini aniqlashdan iborat. Tadqiqot uchun havo kompressori, resiver, rostlash klapani, rotametr, separatsiya kamerasi va fraksiyalarni yig'ish tizimi bilan jihozlangan laboratoriya miqyosidagi pnevmatik separator loyihalashtirildi va sinovdan o'tkazildi. Tajribalar sanoat un ishlab chiqarish jarayonining yakuniy bosqichidan olingan 100 g kepak–un aralashmasi namunalari asosida, 0,56–0,70 m/s oralig'idagi havo oqimi tezliklarida amalga oshirildi. Natijalar unni ajratib olish samaradorligi havo oqimi tezligiga bevosita bog'liqligini ko'rsatdi. 0,56 m/s tezlikda mayda zarrachalarning havo oqimiga qo'shilishi yetarli darajada bo'lmadi, 0,65 m/s dan yuqori tezliklarda esa turbulentlik va yirik kepak zarrachalarining mayda fraksiyaga o'tishi sababli separatsiya selektivligi pasaydi. Eng yuqori samaradorlik 0,62 m/s tezlikda kuzatildi va bunda unni ajratib olish darajasi taxminan 73% ni tashkil etdi. Olingan natijalar havo oqimi tezligini optimallashtirish separatsiya samaradorligini oshirishini, elak yuzalariga tushadigan mexanik yuklamani kamaytirishini hamda pnevmatik un klassifikatsiyasi tizimlarining texnologik samaradorligini yaxshilashini tasdiqlaydi.

Modern flour-milling industries require efficient and energy-saving technologies for separating flour particles from bran mixtures generated during grinding and classification operations. Conventional mechanical sieving systems are widely used in flour production; however, these systems are often associated with rapid wear of sieve surfaces, clogging, increased maintenance costs, and limited efficiency when processing finely dispersed mixtures. In recent years, pneumatic separation technologies have received increasing attention because they enable particle classification according to aerodynamic characteristics without direct mechanical contact [4–6].

Pneumatic separation processes are based on differences in particle size, density, shape, and terminal settling velocity. The efficiency of particle classification depends substantially on airflow hydrodynamics, particle–fluid interactions, and separator geometry.

Previous studies have shown that inappropriate airflow conditions can significantly reduce separation selectivity and increase energy consumption [6–9]. Insufficient airflow velocity results in incomplete entrainment of fine flour particles, whereas excessive airflow intensity may generate turbulent flow conditions and cause uncontrolled transport of coarse particles into the fine fraction [8]. Recent developments in pneumatic conveying and fluidization technologies have improved separation performance in various food-processing and powder-handling industries [5, 8].

Nevertheless, limited research has specifically addressed the optimization of airflow velocity for flour recovery from bran mixtures produced during industrial milling operations. In particular, experimental data on the relationship between airflow velocity and flour extraction efficiency under laboratory-scale pneumatic classification conditions remain insufficient. Accordingly, the objective of the present study is to experimentally determine the optimal airflow velocity that provides maximum flour recovery from bran mixtures while maintaining stable operating conditions and minimizing unnecessary mechanical loading on sieving systems. The results obtained may contribute to the development of more efficient pneumatic classification systems for flour-milling industries.

MATERIALS AND METHODS

2.1 Experimental Setup

A laboratory-scale pneumatic separation unit was designed and assembled for the experimental investigation (Figure 1). The experimental system comprised the following components:

1. Air compressor;
2. Receiver tank;
3. Ball valve for airflow regulation;
4. Rotameter for airflow measurement;
5. Pneumatic separation chamber;
6. Raw-material feeding pipe;
7. Airflow inlet channel;
8. Heavy-fraction outlet;
9. Light-fraction collection chamber.

The separation chamber was manufactured from transparent acrylic material to enable visual observation of particle movement during operation. The internal diameter of the separation chamber was 120 mm, and its height was 850 mm. Compressed air generated by the compressor was supplied to the chamber through the airflow inlet pipe. Airflow velocity was controlled using a regulating valve and measured by a calibrated rotameter. During operation, the bran–flour mixture was introduced into the separation zone, where the particles were classified according to their aerodynamic behavior and terminal settling velocities.

2.2 Raw Material Characteristics

The material investigated in this study consisted of a bran–flour mixture obtained from the final stage of industrial flour milling. The average initial flour concentration in the mixture was approximately 74%.

The average particle-size distribution was as follows:

- flour particles: 80–120 μm;
- bran particles: 250–800 μm.

The moisture content of the material was maintained within the range of 12–13% throughout the experiments to ensure stable aerodynamic behavior. Each experimental run was conducted using a 100 g sample of the mixture.

2.3 Experimental Procedure

The experimental procedure comprised the following stages:

1. Preparation and weighing of the bran–flour mixture;
2. Accumulation of compressed air in the receiver;
3. Adjustment of airflow using the regulating valve;
4. Measurement of airflow velocity using the rotameter;
5. Feeding of the material into the separator chamber;
6. Collection of the heavy and light fractions;

7. Determination of flour concentration in the collected fraction using sieve No. 38.

The experiments were conducted at rotameter readings from 2 to 8, corresponding to airflow velocities ranging from 0.56 to 0.70 m/s. Each experiment was repeated three times to ensure reproducibility of the results. Mean values were used for subsequent analysis. The experimental uncertainty did not exceed ±3%.

THEORETICAL BACKGROUND

The separation of dispersed particles in pneumatic systems is governed by the interaction between aerodynamic drag forces and gravitational forces acting on individual particles [4, 7].

The drag force acting on a particle moving in an airflow can be expressed as:

[The source text ends here; the corresponding formula and subsequent content were not provided.]

$$F_d = \frac{1}{2} C_d \rho A v^2$$

where:

- F_d– drag force (N);
- C_d– drag coefficient;
- ρ– air density (kg/m³);
- A– projected particle area (m²);
- v– airflow velocity (m/s).

The terminal settling velocity of particles may be estimated from the equilibrium between drag and gravitational forces:

$$v_t = \sqrt{\frac{2mg}{C_d \rho A}}$$

Particles with terminal velocities lower than the airflow velocity are transported into the light fraction, while particles with higher settling velocities remain in the coarse fraction. The airflow regime inside the separator may additionally be characterized using the Reynolds number:

$$Re = \frac{\rho v d}{\mu}$$

where:

- Re– Reynolds number;
- d– characteristic particle diameter;
- μ– dynamic viscosity of air.

At low Reynolds numbers, airflow remains predominantly laminar and promotes stable particle classification. However, increasing airflow velocity may result in transition to turbulent flow conditions, causing particle recirculation and deterioration of separation selectivity [8, 9].

RESULTS AND DISCUSSION

The experimental investigation demonstrated that flour recovery efficiency is strongly dependent on airflow velocity. At an airflow velocity of 0.56 m/s, only approximately 40% of fine particles were transported into the light fraction. Under these conditions, the drag force acting on flour particles was insufficient to overcome gravitational settling, resulting in incomplete separation and increased loading of sieve surfaces during subsequent processing stages. An increase in airflow velocity to 0.60 m/s improved the entrainment of fine flour particles. The flour concentration in the light fraction increased to approximately 51%, corresponding to nearly 66% recovery of the initial flour content.

The highest separation efficiency was achieved at an airflow velocity of 0.62 m/s. Under these operating conditions, the flour concentration in the light fraction reached approximately 54%, corresponding to nearly 73% recovery of flour particles from the initial bran mixture.

The identified optimal velocity ensured stable hydrodynamic conditions and effective selective transport of low-density particles. The obtained results are consistent with previous studies on pneumatic particle classification and fluidized systems [6–9], in which transitional flow regimes were found to provide the highest separation selectivity. A further increase in airflow velocity above 0.65 m/s resulted in a gradual deterioration of separation efficiency. At higher velocities, turbulent airflow structures intensified particle recirculation and promoted the entrainment of coarse bran particles into the fine fraction. Consequently, the purity of the recovered flour fraction decreased.

The observed reduction in efficiency at elevated airflow velocities may also be associated with increased turbulent kinetic energy and instability of particle trajectories within the separation chamber. Similar phenomena have previously been reported in pneumatic conveying and powder classification systems [8]. Overall, the experimental results indicate that airflow velocity is the dominant operational parameter affecting flour recovery efficiency during pneumatic separation. The conducted experimental investigation confirmed that airflow velocity significantly affects the efficiency of flour recovery from bran mixtures during pneumatic separation. For the laboratory separator investigated in this study, the optimal airflow velocity was experimentally determined to be 0.62 m/s. Under these operating conditions:

- flour recovery reached approximately 73%;
- stable hydrodynamic conditions were maintained;
- separator productivity was maximized;
- unnecessary mechanical loading on sieving surfaces was minimized.

The obtained results demonstrate the potential of pneumatic separation technologies for improving energy efficiency and reducing mechanical wear in flour-milling industries.

The scientific novelty of the study lies in the experimental determination of the optimal airflow velocity for selective flour recovery from bran mixtures under laboratory-scale pneumatic classification conditions.

Future investigations should focus on:

- CFD simulation of airflow distribution inside the separator;
- AI-based optimization of separator operating parameters;
- investigation of the effects of particle-size distribution;
- energy-efficiency analysis of industrial-scale systems;
- development of intelligent adaptive pneumatic classification systems.

CONCLUSION

The conducted study confirms that pneumatic separation is a scientifically and practically justified approach for recovering flour particles from bran mixtures formed during flour-milling operations. The results show that the efficiency of flour recovery is determined primarily by airflow velocity, since this parameter directly governs the balance between aerodynamic drag and gravitational settling of particles. At insufficient airflow velocity, fine flour particles are not fully entrained into the light fraction, which leads to incomplete separation and increases the load on subsequent sieving operations. Conversely, excessive airflow velocity disrupts selective classification by intensifying turbulence, particle recirculation, and the undesirable entrainment of coarse bran particles into the fine fraction. Thus, the effectiveness of pneumatic separation depends not merely on increasing airflow intensity, but on identifying a stable hydrodynamic regime that enables selective particle transport. The experimental results established that the optimal airflow velocity for the investigated laboratory pneumatic separator is 0.62 m/s.

Under these conditions, the flour concentration in the light fraction reached approximately 54%, while flour recovery amounted to nearly 73% of the initial flour content in the bran mixture. This operating regime ensured stable separation conditions, effective entrainment of low-density fine particles, and reduced unnecessary mechanical loading on sieving surfaces.

The findings also demonstrate that airflow velocities below the optimal level limit flour recovery, whereas velocities above approximately 0.65 m/s reduce separation efficiency due to the development of unstable turbulent structures within the separation chamber.

Therefore, the article substantiates the importance of airflow optimization as a key condition for improving the technological performance of pneumatic flour separation systems. The scientific significance of the study lies in the experimental determination of an optimal airflow velocity for selective flour recovery from bran mixtures under laboratory pneumatic classification conditions. The practical value of the results is associated with the possibility of improving energy efficiency, reducing mechanical wear of sieving equipment, and increasing the operational reliability of flour-milling processes. Based strictly on the findings of the study, further research should be directed toward a more detailed analysis of airflow distribution inside the pneumatic separation chamber using CFD simulation, since the stability of hydrodynamic conditions was shown to be decisive for separation efficiency. In addition, optimization of separator operating parameters through AI-based methods should be considered in order to identify the most effective combinations of airflow velocity and technological conditions.

Future investigations should also examine how particle-size distribution affects separation selectivity, as the interaction between flour and bran particles of different sizes directly influences recovery efficiency. Finally, industrial-scale studies should assess the energy efficiency of pneumatic separation systems and support the development of intelligent adaptive classification technologies capable of maintaining optimal airflow regimes during continuous flour-milling operations.

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EDITORIAL REVIEW

The article entitled "Determination of the Optimal Airflow Velocity for Flour Separation from Bran Mixtures by Pneumatic Separation" addresses a technically relevant problem in flour-milling technology, namely the improvement of flour recovery from bran–flour mixtures through the optimization of airflow velocity in a pneumatic separation system. The topic is timely and practically significant, since conventional mechanical sieving systems are often associated with sieve clogging, mechanical wear, increased maintenance costs, and limited efficiency when processing finely dispersed mixtures. The scientific novelty of the article lies in the experimental determination of the optimal airflow velocity for selective flour recovery from bran mixtures under laboratory-scale pneumatic classification conditions. While pneumatic classification and fluid–particle separation have been widely studied in general powder-processing contexts, the article focuses specifically on flour recovery from bran mixtures, which gives the study a clearly defined technological orientation. The identification of 0.62 m/s as the optimal airflow velocity provides a concrete experimental result that may serve as a basis for further engineering refinement.

The relevance of the research is well substantiated. Flour-milling enterprises require energy-efficient and mechanically reliable separation technologies, and the use of pneumatic separation offers a promising alternative or supplement to conventional sieving. The article convincingly demonstrates that airflow velocity is not merely an auxiliary operating parameter but a decisive factor affecting separation selectivity, flour recovery, and the purity of the fine fraction.

The practical significance of the study is evident from its potential application in improving separator productivity, reducing unnecessary mechanical loading on sieve surfaces, and enhancing energy efficiency in flour-milling operations. The reported flour recovery of approximately 73% at the optimal airflow velocity indicates that the proposed approach may contribute to better utilization of residual flour contained in bran mixtures. The research methodology is generally appropriate for the stated objective. The use of a laboratory-scale pneumatic separator, controlled airflow regulation, rotameter-based measurement, defined sample mass, repeated experiments, and calculation of average values provides a reasonable experimental basis. The description of the separator components and material characteristics strengthens the reproducibility of the study. However, the article would benefit from a more detailed presentation of the statistical treatment of results, including variance, confidence intervals, or graphical representation of experimental trends. In addition, the theoretical section should be completed with the relevant drag-force equation and its connection to the experimental findings. Among the strengths of the article are its clear research objective, logical structure, practical orientation, and experimentally derived optimal parameter.

The discussion also adequately explains why both insufficient and excessive airflow velocities reduce separation efficiency. The main weaknesses are the limited scale of experimentation, the absence of detailed statistical analysis, and insufficient discussion of possible industrial-scale limitations. The article would also be strengthened by a fuller comparison with prior experimental studies and by inclusion of energy-consumption data. In conclusion, the article represents a scientifically grounded and practically useful contribution to pneumatic flour separation research. Subject to minor technical and editorial improvements, it is recommended for publication in a scientific journal.