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CRITICAL REVERSE FLUIDIZATION VELOCITY OF THE SELECTED VEGETABLES

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ABSTRACT

The objective of this paper was to study a possibility to use existing models for determination of the minimum fluidization velocity during freezing fruits and vegetables by reverse fluidization. French fries, Brussels sprouts, broccoli florets, carrot in the form of a cube with sides of 1 cm and slices with dimensions of 3x3x0.5 cm were used to form frozen material. Values of the minimum fluidization velocity were measured by means of an anemometer. The results of calculation from four calculation models of the minimum fluidization velocity were compared to the values obtained experimentally. The calculated values were affected by average errors from 24% in case of a carrot cube to 224% in case of broccoli florets. There was no statistical difference between the results obtained between the tested models.

The list of symbols:

A – surface area, (m^2)
d – diameter of a particle, characteristic dimension of a product, (m)
F – fluid pressure force, (N)
g – gravitational acceleration, ($m \cdot s^{-2}$)
G – gravity, (N)
L – length, (m)
m – mass, (kg, g)
P, ΔP – pressure, difference in pressure, (Pa)
S, S_1, S_2 – distance between nozzles, (mm)
V – volume, (m^3)

w – velocity, ($m \cdot s^{-1}$)
ε – porosity of a bed
μ – dynamic viscosity of air, (Pa·s)
ν – kinematic viscosity of air, ($m^2 \cdot s^{-1}$)
ρ – density, ($kg \cdot m^{-3}$).

Indexes:

f – fluid
mf – minimum fluidization
p – initial
rz – actual
s – solid body
z – substituting

Similarity numbers:

Ar – Archimedes number, $Ar = \frac{g \cdot d^3 \cdot \rho_f (\rho_s - \rho_f)}{\mu_f^2}$

Re – Reynolds number, $Re = \frac{w \cdot d}{\nu}$

Introduction

Fluidization is one of the most important unit operations used currently in agricultural engineering. Advantages of this process caused that it is widely used in such sectors of industry as: power industry, dehydration industry and from the beginning of the 60's also in refrigeration.

Generally, the fluidization phenomenon requires fluid pressure on the surface of a bed to be equal to the resultant of gravity and buoyant forces (Kawamura and Suezawa, 1961). Gravity of a bed equals to:

$$G = (\rho_s - \rho_f) \cdot g \cdot V \cdot (1 - \varepsilon) \tag{1}$$

The fluid pressure force may be calculated from the modified Darcy-Wesibach equation (Niven, 2002):

$$F_w = f \cdot \frac{V}{d_z} \cdot \frac{1 - \varepsilon}{\varepsilon^3} \cdot w_{mf}^2 \cdot \rho_f \tag{2}$$

In this equation *f* stands for a flow resistance coefficient. This coefficient, independently from the fluid flow type, was determined by Ergun (1952) as:

$$f = \frac{150 \cdot (\rho_s - \rho_f) \cdot \mu}{d_z \cdot \rho_f \cdot w} + 1{,}75 \quad (3)$$

If the fluid pressure force is lower than the gravity of a bed then the fluid flows through channels between immovable particles. The fluid pressure decrease is proportional to its velocity (fragment 0-A) (fig.1). When the fluid pressure on the bed surface is equal to the static pressure (point A), an immovable bed turns into a fluidized state. The fluid velocity in this point marked with w_{mf} is called the minimum fluidization velocity. During further increase of velocity the fluid pressure on the bed surface is higher than its static pressure. The layer expansion and the increase of the bed porosity takes place (fragment B-C). Decrease of pressure is constant within the entire fluidization. It is related to balancing the increase in the bed porosity with its increased turbulence (Yang, 1998; Gruda and Postolski, 1999; Kmieć et al., 2007).

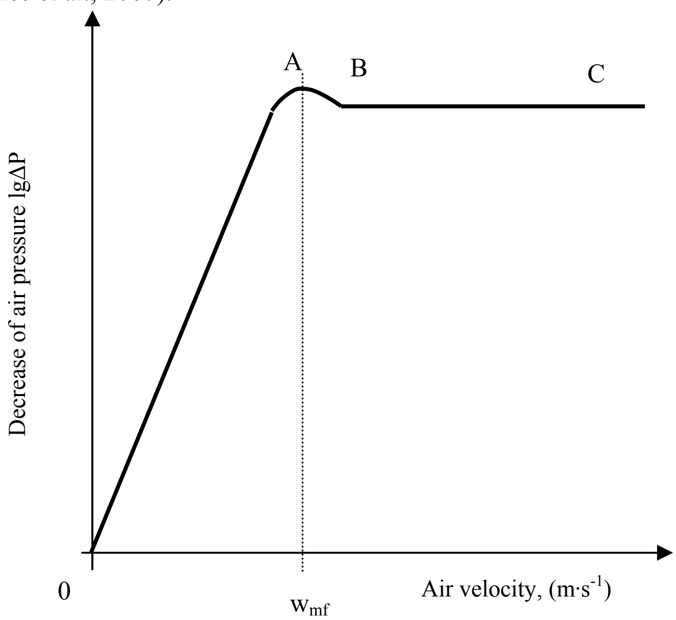

Figure 1. Dependence of pressure drop on velocity of gas stream flowing through the bed

A necessary condition of the product bed fluidization is that the bed velocity is equal to or higher than the velocity of the minimum fluidization. This velocity depends on, inter alia, a particle diameter and porosity of a bed (Gruda and Postolski, 1999).

A reversed fluidization is a specific variety of fluidization. In this method, an impingement phenomenon is used for causing fluidized boiling of the product bed. In this method, with the moment of achieving the minimum velocity of fluidization, the air buoyant force is higher than the product gravity and the product is floated towards the fountain top. Then, as a result of mutual influence of the neighbouring particles of a product, single particles are placed on the edge of the fountain top and get to the zone of lower air pressure or under the stream of air flowing out of a nozzle. It causes their dropping to the bottom of a working chamber of a device and a new process cycle begins (fig. 2).

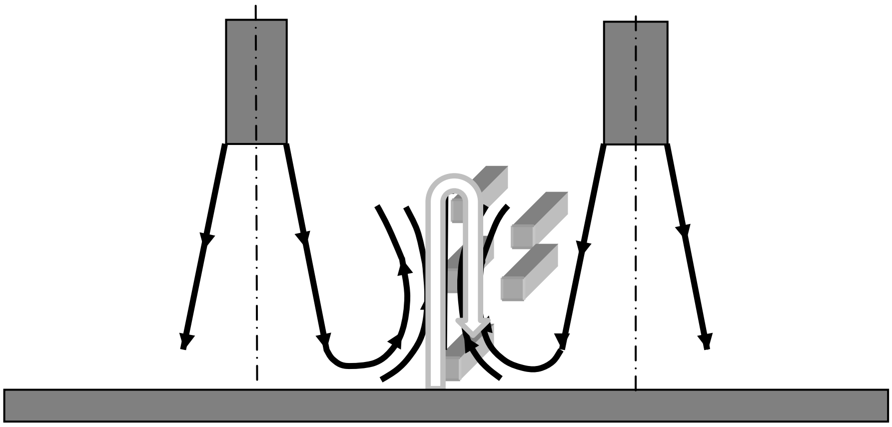

Figure 2. Motion of bed particle under reverse fluidization

There are many formulas for determination of the minimum velocity of fluidization. However, they are developed for other sectors of industry than the food industry and they do not include such properties of agricultural and food products as e.g. irregularity of the shape or adhesion forces. In practice, majority of solutions to this problem origins in Ergun's equation (3) (Ergun, 1952):

$$\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{w\cdot\mu}{\phi^2 d^2} + 1{,}75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{w^2\rho}{\phi^2 d} \tag{4}$$

Where ϕ is a coefficient of the bed particle shape and decrease of pressure on the length L ($\frac{\Delta P}{L}$) may be determined as:

$$\frac{\Delta P}{L} = (1-\varepsilon)(\rho_s - \rho_f)g \tag{5}$$

In order to simplify the equation (4) in many studies, Wen's and Yu's approximations are used (Niven, 2002):

$$\frac{1-\varepsilon}{\phi^2\cdot\varepsilon^3} \approx 11 \text{ and } \frac{1}{\phi\cdot\varepsilon^3} \approx 14 \tag{6}$$

The use of these constants leads to simplification of Ergun's equation (4) to the following form (Dechsiri, 2004):

$$Re_{mf} = \frac{d \cdot w \cdot \rho_f}{\mu} = \sqrt{33{,}7^2 + 0{,}0408 \frac{d^3 \cdot \rho_f \cdot (\rho_s - \rho_f) \cdot g}{\mu^2}} - 33{,}7 \quad (7)$$

The above formula is used in cases of powder beds fluidization. With reference to the fluidizing bed of carbon in high air pressures, Chitester et al. (1984) suggested modification of Ergun's equation through the use of constants 28.7 and 0.494:

$$Re_{mf} = \sqrt{28{,}7^2 + 0{,}494 \frac{d^3 \cdot \rho_f \cdot (\rho_s - \rho_f) \cdot g}{\mu^2}} - 28{,}7 \quad (8)$$

In calculations related to the minimum velocity of fluidization in cooling or freezzing conditions of food, many authors recommend the use of Todes's formula (Todes and Tsitovich, 1981):

$$Re_{mf} = \frac{Ar}{1400 + 5{,}22\sqrt{Ar}} \quad (9)$$

or Kuni's and Levenspiel's formula (Gruda and Postolski 1999):

$$w_{mf} = \sqrt{\frac{d \cdot (\rho_s - \rho_f) \cdot g}{24{,}5 \cdot \rho}} \quad (10)$$

Selection of an appropriate equation for determination of the minimum velocity of fluidization of food products even in case of a classic fluidization is not easy on account of a varied shape and size of products. Theoretical determination of the velocity of the minimum fluidization in the reverse fluidization method has not been investigated so far. Thus, the objective of the paper is to find a solution, which would enable determination of the minimum velocity of fluidization of vegetables during their freezing by means of the reverse fluidization method.

Methodology

The research was carried out on a prototype laboratory device which allowed realization of cooling processes with the reverse fluidization method. A working chamber of the device was equipped with a replaceable head consisting of a tube sheet with nozzles located in it with 370 mm length and the internal diameter of 18 mm (fig. 3). There were 20 nozzles in the head and their distribution was respectively S1 = 50 mm and S2 = 47 mm. This head was selected as a result of optimization research, which was previously carried out (Góral and Kluza, 2012).

Measurements were carried out in the environmental temperature of –22ºC at the scope of the reflected air velocity from 2 $m \cdot s^{-1}$ to 12 $m \cdot s^{-1}$. Distance from the working chamber bottom to the nozzles was fixed and it was 120 mm. The raw material used in the research consisted of French fries of a cross section of 1 cm x 1 cm and a varied length, carrot cut in cubes of a 1 cm side and slices of 3 cm x 3 cm and thickness of 0.5 cm, Brussels sprouts of a diameter from 2 cm to 3.5 cm and broccoli florets.

Products were fresh, no traces of mechanical damages or infection were reported.

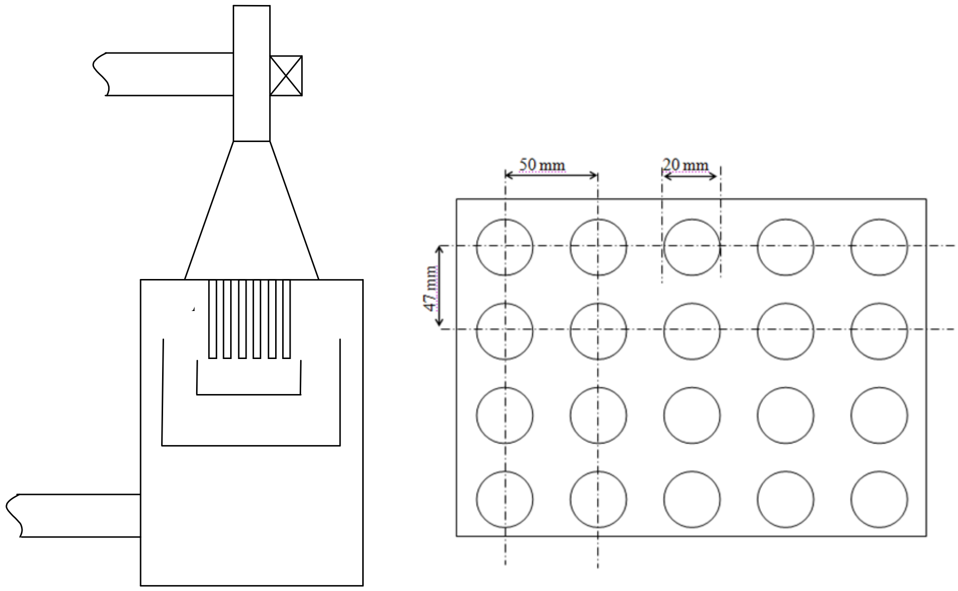

Figure 3. Scheme of test rigs with cross section of operating head

Since, the investigated products came from various classification groups, the course of their preparation was varied. The test was prepated generally by removing an external cover, washing in water in order to remove peeling remains and then cutting into cubes, columns or slices. Before fluidization, raw materials were weighed on an electronic scale and raw material volume was measured. On this basis, the raw material density was determined. A balanced diameter of raw material was calculated from the formula $d_e = 1{,}24\sqrt[3]{V}$ (Gruda and Postolski, 1999; Jaros and Pabis, 2006). Samples, prepared this way, of the mass of approx. 0.5 kg each were subjected to fluidization. Experiments were carried out in three repeats. In conditions of fluidization in a bed, velocities of air reflected from the working chamber bottom, its temperature and moisture were measured. Measurements were carried out with the use of KIMO Anemo-Manometer MP 120 with a Pilot tube L type with the outside diameter of 6 mm. The remaining air parameters required for calculations were accepted from moist air tables (Pawiłojć et al., 1998). The theoretical minimum velocity of fluidization was calculated from formulas (7), (8), (9) and (10) and the obtained values were compared to the results obtained from experiments with the use of Statistica 10.0 statistical packet.

Research results and discussion

The experimental test allowed determination of the critical velocity of the early stage of fluidization of the selected vegetables (fig. 4). The highest minimum fluidization velocity during freezing with the reversed fluidization method was with regard to broccoli florets (11 m·s^{-1}). The lowest velocity of the minimum fluidization was measured during carrot cube treatment (2,5 m·s^{-1}). According to predictions, this velocity depended mainly on the diameter of the bed element.

Figure 4. View of the bed of carrots cubes under fluidization

Values of the minimum fluidization velocity of French fries, Brussels sprouts and broccoli florets obtained through calculations with the use of formula (7-10) considerably differed from experimental results (figure 5). Average values calculated for those raw materials were within 161% and 224% from the measured values. However, while comapring the minimum velocity of fluidization of carrot cubes and slices obtained by experiments and calculated values, deviation did not exceed 30%.

Then, a statistical significance of differences of values obtained acc. to particular calculations models, was investigated. Firstly, Fischer's test was carried out in order to investigate variability of variance. Results of this test were presented in table 1.In each analysed case the value p was higher than α=0.05, thus variability of variance was not statistically significant. Therefore, the t-Student test, which assumed equal variances in order to investigate the significance of differences between the particular values obtained from calculations, could be carried out. Values obtained acc. to this test were presented in table 2.

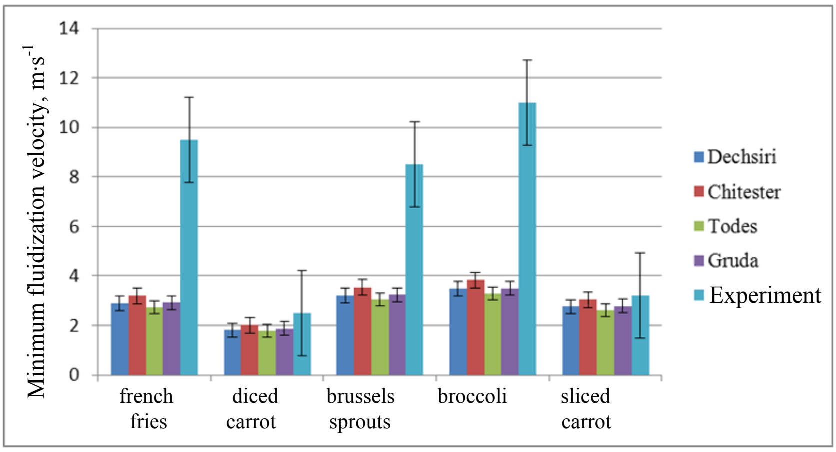

Figure 5. Minimum fluidization velocity of selected vegetables which were determined using four models in comparison with experimental data

Table 1
The p values which were obtained in Fischer's test

	Dechsiri	Chitester	Todes	Gruda
Dechsiri		0.44191	0.41279	0.34568
Chitester	0.44191		0.35739	0.29447
Todes	0.41279	0.35739		0.42936
Gruda	0.34568	0.29447	0.42936	

Table 2
The p values which were obtained in t-Student's test

	Dechsiri	Chitester	Todes	Gruda
Dechsiri		0.70272	0.867159	0.710021
Chitester	0.70272		0.576874	0.943268
Todes	0.867159	0.576874		0.557300
Gruda	0.710021	0.943268	0.557300	

When analysing the t-Student's test results it was found out that the value p for each method was higher than the assumed $\alpha=0.05$ which proves that there were no significant differences between the values calculated according to each method.

To conclude, the value of the minimum fluidization velocity calculated and determined by means of experiments was the most similar to the beds comprising of cubed and sliced carrot. With respect to the treatment of French fries, broccoli florets and Brussels sprouts, measurements of the value of this velocity may be burdened with a significant error. It is related to the specificity of this raw material. The shape of French fries considerably differs from the ball shape accepted for the research. Thus, French fries require considerably higher air velocity to initialize fluidization. Whereas, the Brussels sprouts bed consisted of single elements with the varied size. In calculations of the minimum velocity of fluidization, an average diameter of Brussels sprouts was assumed as a diameter of the bed element. This, certainly influenced divergence between calculations results and the measured values. Similarly, a considerable divergence between the calculated results and experimentally determined of the minimum fluidization velocity of broccoli florets, was reported. It was caused by not only high variability of the size and shape but also by significant difference of the mass of particular florets.

Conclusions and statements

Values of the minimum velocity of fluidization determined experimentally ranged from 2.5 m·s-1 for the bed of cubed carrots to 11 m·s-1 for the bed of broccoli florets.

The calculations of the minimum velocity of fluidization carried out by means of four methods (Dechsiri, Chitester, Todes and Gruda) were burdened with average deviations from the value of the ones obtained by means of experiments from 24% in case of cubed carrot to 224% with regard to the beds of broccoli florets. Such significant deviations were the most probably caused by approximation of the French fry and broccoli shape to a ball shape and in case of Brussels sprouts - assuming for calculations an average diameter of a product. The statistical analysis carried out by the t-Student's test, which assumed equality of variance, confirmed that there were no significant differences between the values of the minimum velocity of fluidization calculated with particular methods in each investigated case of fluidization.

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PRĘDKOŚĆ KRYTYCZNA ODWRÓCONEJ FLUIDYZACJI WYBRANYCH WARZYW

Streszczenie. W pracy analizowano możliwość wykorzystania istniejących modeli wyznaczania minimalnej prędkości fluidyzacji podczas zamrażania owoców i warzyw metodą odwróconej fluidyzacji. Złoża poddawane zamrażaniu formowano z frytek ziemniaczanych, brukselki, różyczek brokułu, marchwi w postaci kostki o boku 1 cm i plastrów o wymiarach 3x3x0,5 cm. Wartości minimalnej prędkości fluidyzacji wyznaczano przy pomocy anemo-manometru. Wyniki z badań eksperymentalnych porównywano z wartościami uzyskanymi z 4 modeli obliczeń minimalnej prędkości fluidyzacji. Obliczone wartości obarczone były średnimi odchyleniami od wartości uzyskanych eksperymentalnie, od 24% w przypadku marchwi w kostce do 224% w przypadku złóż różyczek brokułu. Jednocześnie stwierdzono brak statystycznych różnic pomiędzy wynikami uzyskanymi wg badanych modeli.

Słowa kluczowe: minimalna prędkość fluidyzacji, odwrócona fluidyzacja, zamrażanie, warzywa