Bulletin of the *Transilvania* University of Braşov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 5 (54) No. 1 - 2012

THE EFFECT OF SOLID PARTICLE SIZE UPON TIME AND SEDIMENTATION RATE

M. MARINUC[1] F. RUS[1]

Abstract: *In any application, the sizes of the particles to be removed from the mixtures heterogeneous determine, to a large extent, the method to be used for their separation. The literature reveals that the cyclone efficiency and implicitly the sedimentation rate is dependent on the particle size from the mass of heterogeneous solid-fluid mixtures. The objective of this paper is to theoretically demonstrate the influence of the solid particle dimensions on the sedimentation rate in centrifugal field, inside the cyclone and the time influence on sedimentation in the two sedimentary regimes.*

Key words: *particles size, sedimentation rate, cyclone.*

1. Introduction

There are many cases during the processing and handling of particulate solids when particles are required to be separated from suspension in a gas.

In any application, the size of the particles to be removed from the gas determines, to a large extent, the method to be used for their separation. Generally speaking, particles larger than about 100 µm can be separated easily by gravity settling. For particles less than 10 µm more energy intensive methods such as filtration, wet scrubbing and electrostatic precipitation must be used.

The principle of separation in a cyclone is to increase the effect of sedimentation by centrifugal force, which is achieved by introducing tangential suspension in a device. The efficiency of separation cyclones is much higher than dusting rooms because in a centrifugal force field, the effect of separation is maximized.

In the case of cyclones, the effect of centrifugal force manifests itself differently from particles and gas. Due to centrifugal force the solid particles are thrown to the wall where they lose energy and fall moving under the action of gravity at the bottom of the device where it is discharged (particle mass > gas mass). So, gas is moving in a downward spiral, solid particles being driven to the top of the gas and then gas (air) is discharged through the central tube of the cyclone due to the circulation effect [1].

The most common type of cyclone is known as the reverse flow type (Figure 1). Inlet gas is brought tangentially into the cylindrical section and a strong vortex is thus created inside the cyclone body. Particles in the gas are subjected to centrifugal forces which move them radially outwards, against the inward flow of gas and towards the inside surface of the cyclone on which the solids separate. The direction of flow of the vortex reverses near

[1] Dept. of Engineering and Management in Food and Tourism, *Transilvania* University of Braşov.

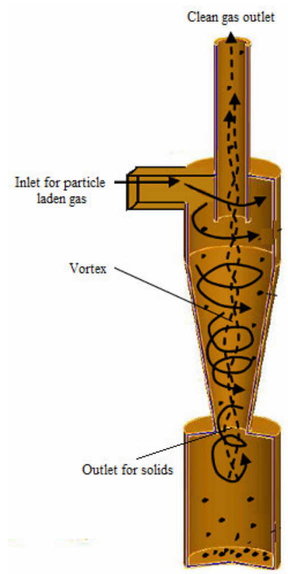

Fig. 1. *Schematic diagram of a reverse flow cyclone separator*

the bottom of the cylindrical section and the gas leaves the cyclone via the outlet in the top (the solids outlet is sealed to gas). The solids at the wall of the cyclone are pushed downwards by the outer vortex and out of the solids exit. Gravity has been shown to have little effect on the operation of the cyclone [3].

One of the determinants of separation of heterogeneous systems by the action of gravity is the sedimentation rate.

2. Sedimentation Rate

Once the forces acting on a particle are balanced, the particle motion becomes a uniform movement (particle falls into the medium at a constant speed), the speed of the particle being called sedimentation rate.

Sedimentation rate in the centrifugal force field in the cyclone is determined by the same reasoning as in the centrifugal sedimentation field, of devices with rotating elements.

To be applied to the cyclone, centrifugal acceleration in these relations is expressed in terms of speed v_0, speed at which the heterogeneous mixture enters the cyclone through the inlet:

$$a_c = w_0^2 \cdot R_0 = v_0^2 / R_0, \qquad (1)$$

where R_0 is the radius of the circular path described by the particles when entering inside the cyclone body through the inlet feed, [m]; w_0 - angular velocity; v_0 - peripheral velocity of a particle in suspension in the cyclone inlet, [m/s] (Figure 2).

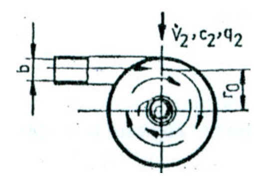

Fig. 2. *Horizontal section through the cyclone*

If in the relations used to determine sedimentation rate, for the case of flow characteristic regimes, the centrifugal acceleration formula is introduced, expressed in terms of peripheral speed, we obtain relations for the calculation of the sedimentation rate:

- laminar regime of sedimentation, when Ar · Fr < 36:

$$v_{scl} = \frac{1}{18} \cdot \frac{d^2}{\upsilon} \cdot \frac{\rho_p - \rho_m}{\rho_m} \cdot \frac{v_0^2}{R}, \qquad (2)$$

where: d is the diameter of the particle, [m]; v - cinematic viscosity, [m^2/s]; ρ_p, ρ_m - particle density and environment density, [kg/m^3]; v_0 - peripheral velocity of a particle in suspension in the cyclone inlet, [m/s];

- intermediate regime of sedimentation, when 36 <Ar · Fr < 84500:

$$v_{sci} = 0.152 \cdot \frac{w^{1.428} \cdot R^{0.714}}{\upsilon^{0,43}} \cdot d^{1.143} \cdot \left(\frac{\rho_p - \rho_m}{\rho_m}\right)^{0.714}; \qquad (3)$$

• turbulent regime of sedimentation, when Ar · Fr > 84500:

$$v_{sct} = 1.74 \cdot v_0 \cdot \sqrt{\frac{d}{R} \cdot \frac{\rho_p - \rho_m}{\rho_m}}. \tag{4}$$

To determine the time of sedimentation one must apply the reasoning used and consider that the sedimentation rate is space derivative with respect to time and that the moving particles to the place of sedimentation is carried out on radial directions:

$$v_{sc} = \frac{\mathrm{d}R}{\mathrm{d}t}. \tag{5}$$

If we separate variables and if sedimentation rate is replaced by one of the relations derived for the characteristic regimes of sedimentation, differential equations are obtained and by integrating the resulting expressions which calculate the sedimentation time for each of these characteristic regimes. Based on this reasoning we obtain:

• for the laminar regime of sedimentation, the sedimentation time expression is:

$$t_s = \frac{9\upsilon}{d^2 \cdot v_0{}^2} \cdot \frac{\rho_m}{\rho_p - \rho_m} \cdot (R_2{}^2 - R_1{}^2)\,; \tag{6}$$

• for the turbulent regime of sedimentation, sedimentation time is:

$$t_s = \frac{R_2^{1.5} - R_1^{1.5}}{2.55 \cdot v_0 \cdot \sqrt{d \cdot \frac{\rho_p - \rho_m}{\rho_m}}}. \tag{7}$$

In the above relations R_1 is the surface radius of separation, which is considered equal to the outlet orifice radius of solid phase; R_2 - inner radius of the cylindrical part of cyclone.

The analysis of relation (6) and (7) shows that sedimentation rate is even greater as the radius R_2 of cyclone is bigger and as the velocity input of the heterogeneous mixture is lower.

To determine the transit time inside the cyclone, it is considered that the path length traveled by the particle from the moment of entry into the cyclone and until total sedimentation, can be calculated by:

$$L = \varphi \cdot R, \tag{8}$$

where φ is the angle at the center corresponding to the spiral trajectory described by particles from the moment of their entry into cyclone until sedimentation; R - average radius of the trajectory: $R = (R_1 + R_2) / 2$.

The angle φ is determined by the relationship:

$$\varphi = 2 \cdot \pi \cdot n, \tag{9}$$

where n is the number of rotations around the axis of symmetry of the cyclone.

Experimental investigations revealed that from the entry into the cyclone and until sedimentation the particles perform 4 to 5 complete rotations around the axis of symmetry of the cyclone, ($n = 1.5 – 5$).

Numbers of turns that particles had performed inside the cyclone until sedimentation were determined from traces left by them on the inner walls of the cyclone.

If replacements are made in (8), the path length traveled by the particles is:

$$L = \pi\,(R_1 + R_2) \cdot n\,. \tag{10}$$

Considering that at the entry into the cyclone inlet the heterogeneous mixture has linear velocity v_0 and particles retain this velocity along the path length L, the transit time of particles in the cyclone is:

$$t_1 = \frac{L}{v_0} = \frac{\pi(R_1 + R_2) \cdot n}{v_0}. \tag{11}$$

To achieve sedimentation, the condition that the sedimentation time is less than the transit time of particles in the cyclone must be fulfilled, i.e.: $t_s > t_1$, and if in this relationship the analytical expressions that determine the duration of sedimentation and transit in cyclone for the characteristic regimes are replaced, we obtain mathematical relationships which determine the critical diameter (minimum) of particles that are separated during the flow regimes [4].

3. Material and Method

For the theoretical investigation regarding the influence of particle size over the sedimentation rate in centrifugal field inside the cyclone, the dimensions of the intermediate products resulting from the grist were used [2].

To calculate the sedimentation rates in the centrifugal field the following relationship were used: (2), (4); and for calculating the sedimentation time corresponding for the two sedimentation regimes we used the relations (6) and (7).

In Table 1 the values obtained by sedimentation rate calculation for the two regimes of sedimentation for five values of particle diameters are recorded: $d_1 = 0.000040$ m; $d_2 = 0.000045$ m; $d_3 = 0.000056$ m; $d_4 = 0.000066$ m and $d_5 = 0.000090$ m. In Table 1, d there is the diameter of flour particles, in [m]; ρ_p - flour solids density, in [kg/m^3]; ρ_f - air density, in [kg/m^3]; v_0 - heterogeneous mixture inlet velocity in the cyclone inlet, in [m/s]; η - dynamic viscosity of air, in [N·s/m^2]; υ - cinematic viscosity of air, in [m^2/s]; R_1 - surface radius of separation, which is considered equal to the outlet orifice radius of solid phase, in [m]; R_2 - inner radius of the cylindrical part of cyclone, in [m]; v_{st} - sedimentation rate in the turbulent regime, in [m/s]; v_{sl} - sedimentation rate in the laminar regime, in [m/s].

In Table 2 the values obtained by sedimentation time calculation for the two regimes of sedimentation for the five values of particle diameters mentioned above are recorded. In this table, with t_{sl} we note the sedimentation time in the laminar regime and with t_{st} we denominate the sedimentation time in the turbulent regime.

Sedimentation rates values Table 1

d [m]	**0.00004**	**0.000045**	**0.000056**	**0.000066**	**0.00009**
ρ_p [kg/m^3]	550	550	550	550	550
ρ_f [kg/m^3]	1.2	1.2	1.2	1.2	1.2
v_0 [m/s]	18	18	18	18	18
η [Pa · s]	$18.25 \cdot 10^{-6}$	$18.25 \cdot 10^{-6}$	$18.25 \cdot 10^{-6}$	$18.25 \cdot 10^{-6}$	$18.25 \cdot 10^{-6}$
υ [m^2/s]	0.00001521	0.00001521	0.00001521	0.00001521	0.00001521
R_1 [m]	0.0305	0.0305	0.0305	0.0305	0.0305
R_2 [m]	0.12	0.12	0.12	0.12	0.12
v_{st} [m/s]	12.2286	12.9704	14.4691	15.7079	18.3429
v_{sl} [m/s]	7.217	9.1341	14.1455	19.6485	36.5365

Sedimentation time values Table 2

d [m]	0.00004	0.000045	0.000056	0.000066	0.00009
t_{sl} [s]	0.0077	0.0061	0.0039	0.0028	0.0015
t_{st} [s]	0.0346	0.0367	0.0409	0.0444	0.0519

4. Results and Discussions

To highlight the influence of particle size on sedimentation for the two regimes of sedimentation, data obtained from calculations were processed and graphs were drawn in Figures 3 and 4 using the computer program Microsoft Office Excel 2003.

The chart from Figure 3 showed the influence of solid particle dimensions over the sedimentation rate in centrifugal field in the turbulent regime inside the cyclone separator. It can be observed that the lowest sedimentation rate in the turbulent regime was obtained for the smallest diameter 0.000040 m and the highest sedimentation rate was obtained for the bigger diameter 0.00009 m.

The chart from Figure 4 showed the influence of solid particle dimensions over the sedimentation rate in centrifugal field in the laminar regime inside the cyclone separator. It can be observed that for a diameter of 0.00004 m, a sedimentation rate of 7.217 m/s was obtained, and for a diameter 0.00009 m a sedimentation rate of 38.537 m/s was obtained.

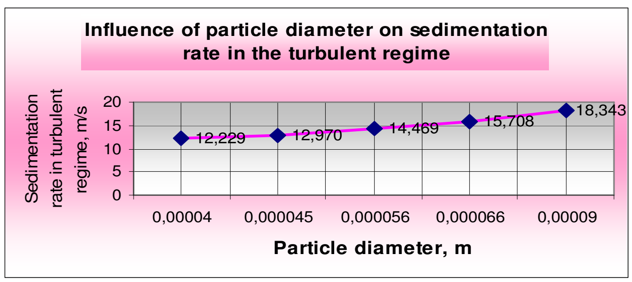

Fig. 3. *Influence of particle diameter on sedimentation in the turbulent regime*

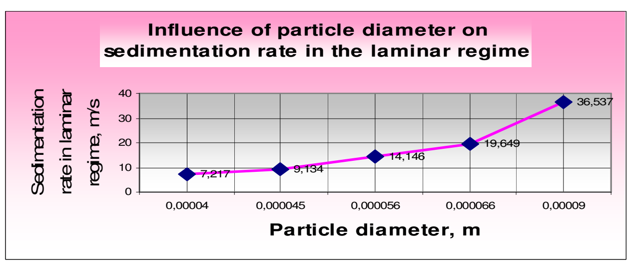

Fig. 4. *Influence of particle diameter on sedimentation in the laminar regime*

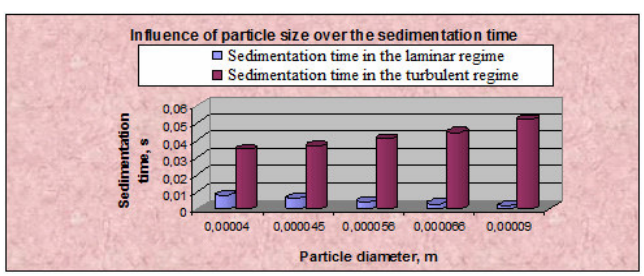

Fig. 5. *Influence of particle size over the sedimentation time in the two regimes of sedimentation*

The chart from Figure 5 showed the influence of particle dimension on the sedimentation time inside the cyclone in both sedimentation regimes, either laminar or turbulent. It can be seen that sedimentation time in the turbulent regime is greater than the sedimentation time in the laminar regime of sedimentation in the centrifugal field.

5. Conclusions

• In the case of turbulent sedimentation regime, sedimentation time is even greater as the solid particle diameter is greater, while in the case of the laminar sedimentation regime, sedimentation time is greater when the solid particle size is smaller.

• Sedimentation rate in the laminar and turbulent sedimentation regime is directly proportional to the solid particle size that is separated inside the cyclone separator.

• In the case of influence of solid particle size over the sedimentation rate, it can be observed that for the same diameter of 0.000040 m, a value of sedimentation rate in the turbulent sedimentation regime of 12.229 m/s was obtained and for the laminar sedimentation regime, a value of sedimentation rate of only 7.217 m/s was obtained. Great differences can be observed in the case of diameter 0.00009 m, for which, a value of sedimentation rate in the laminar regime of 38.537 m/s was obtained, a rather high value in comparison with the sedimentation rate in the turbulent regime which was of 18.343 m/s.

Acknowledgements

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POS-DRU: ID 59321.

References

1. Ivan, E., Craiu, I.: *Operations and Equipment in Food Industry.* Timişoara. Publisher Mirton, 2003.
2. Lupea, A.: *Technologies in Food Industry*. Timişoara. Technical University, 1995.
3. Martin, R.: *Introduction to Particle Technology. Second Edition.* Australia. John Wiley & Sons Ltd, 2008.
4. Rus, F.: *Separation Operations in the Food Industry.* Braşov. *Transilvania* University Press, 2001.