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AERODYNAMIC AND SOLIDS CIRCULATION RATES IN SPOUTED BED DRYING OF CARDAMOM (Part 2)

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Abstract: Two dimensional spouted bed units with flexible bed dimensions were used with draft tubes to study spouting pressure drop and minimum spouting velocity, solids circulation rate and average cycle time. The data were collected while varying slant angle, draft tube height, separation distance and height of bed using cardamom. The variables which affect the spouting pressure drop and airflow through the beds are discussed. Empirical correlations were developed following the principles of dimensional analysis and similitude. The developed correlations were in accordance with the collected data. The article has been divided into two parts where the first part includes the analysis for spouting pressure drop and minimum spouting velocity and the second parts includes the solids circulation rate and average cycle time.

Key words*: Spouting pressure drop, minimum spouting velocity, solids circulation rate, average cycle time, dimensional analysis, Elettaria cardamomum, Conical-Cylindrical Spouted Bed (CSB), curing chambers, rectangular orifices*

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INTRODUCTION

Spouted bed technology is very useful for drying solids that are sticky, have irregular texture and vary widely in particle size distribution. Application of vigrous movements of solids in spouted bed helps in uniform drying but the performance depends widely on the cyclic movement of the solid particles and also on the properties related to solid circulation such as cycle time and fraction of this time spent in the spout and annular zones [1]. The solid circulation rate in a two dimensional spouted bed dryer is estimated using the particle velocity above the cone and the paricle voidage in the spout or in the downcomer [2]. In the spout, the particle velocity is measured by tracking the particle but in the downcomer the particle velocity is influenced by the inlet air velocity, the inlet nozzle width, spout width and the separation distance between the draft tubes. Several researchers have tried to develop mathematical models for solid circulation rate, but they lack a soud understanding of parametric relationships. Hence for a two dimensional spouted bed dryer it is important to conduct proper experimental studies to explain the relation between factors and how they are influenced by the presence of draft tubes.

In a spouted bed dryer the continous movement of particles between the spout and the downcomer has a significant effect on the its performance. In 1959 Thorley, *et al.* [6] investigated conical-cylindrical spouted beds without draft tubes indicating that the cycle time can be quantified with or without solid circulation rate in conjugation with particle properties, bed geometry and volumetric gas flow. They calculated the mean cycle time by dividing the total mass of particles in the bed by the solids circulation rate. The approach appllied by Thorley *et al.* (1959) [6] agrees well with measured values and are compatible for estimation of cycle time [2].

In the present study, parameters such as spouting pressure drop, minimum spouting velocity, solid circulation rate and average cycle time have been considered for the development of mathematical models based on dimensional analysis and similitude principles for a batch type slotted 2DSB with draft tube [3-5]. In part 1 of the study we analaysed mathematical models based on spouting pressure drop and minimum spouting velocity. The intent of Part 2 of the study is to investigate the influence of solids circulation rate and average cycle time on the spouting characteristics of spouted bed with draft tube while taking into account grain particle parameters in order to provide a sound basis for the design of commercially viable units.

MATERIAL AND METHODS

Details on the theory and model development are provided in the Part 1 of the study. The assumptions made to generate mathematical models for solids circultation rate and average cycle time are same as mentioned in Part 1 of the study. Tables 1 and 2 represent the pertinent and repeating variables considered for the mathematical modeling.

The chosen variables were convenient for the experimental and analytical phase of the study. The time taken by particles to make the journey from the top of the down comer back to their starting point is of considerable interest in solids mixing, heat treatment and drying applications. Previous studies have shown that the proportion of time spent by a particle in the draft tube is insignificant compared to time spent in the down comer [6-8]. Hence, the average cycle time should be dependent on the total mass of solids in the bed, the solids circulation rate, width of the down comer, slanting angle and normal distance. Other factors, which may affect the average cycle time, may be airflow and some material properties.

Table 1. The pertinent variables for the mathematical modeling of fluid and particle dynamics in the 2DSB with draft tube

Symbol	Variable	Unit
P_s	Spouting pressure drop	Pa
U_f	Minimum spouting velocity	$m\cdot s^{-1}$
ρ_ϕ	Dry air density	$kg\cdot m^{-3}$
μ	Absolute viscosity	$kg\cdot m^{-1}s^{-1}$
g	Acceleration due to gravity	$m\cdot s^{-2}$
V_p	Average particle velocity	$m\cdot s^{-1}$
Q_p	Volumetric flow rate of grains	$m^3\cdot s^{-1}$
S_p	Solids circulation rate	$kg\cdot s^{-1}$
M_p	Mass of grains in the spouted bed	kg
t_c	Average cycle time	s
d_p	Geometric diameter of particle	m
ϕ	Sphericity	--
ρ_β	Bulk density of grains	$kg\cdot m^{-3}$
ρ_π	Particle density of grains	$kg\cdot m^{-3}$
E_v	Bed voidage	---
W_b	Width of spouted bed	m
W_d	Width of a down-comer of spouted bed	m
L_b	Length of spouted bed	m
H_b	Depth of grains in spouted bed	m
H_t	Height of draft tube	m
D_i	Diameter of air entry slot	m
θ_σ	Slant angle	--
D_s	Diameter of draft tube or spout	m
W_o	Normal distance	m

Table 2. Repeating variables for the mathematical models and variables representing mass, length and time

Symbol	*Mathematical models*				
	P_s	U_f	S_p	t_c	
ρ_ϕ	-	+	+	-	
g	+	+	+	-	
S_p	-	-	-	+	
M_p	-	-	-	+	
d_p	-	+	-	+	
ρ_π	+	-	-	-	
H_t	+	-	-	-	
W_o	-	-	+	+	
	L	H_t	d_p	W_o	d_p
	M	$\rho_\pi H_\tau^3$	$\rho_\phi \delta_\pi^3$	$\rho_\phi \Omega o^3$	M_p
	T	$(H_t/g)^{1/2}$	$(d_p/g)^{1/2}$	$(W_o/g)^{1/2}$	S_p/M_p

+ = *Variable in the theoretical model,*
- = *Variable not in the theoretical model*

The variables that were important for the analysis of air and solids dynamics were selected. A list of variables for the mathematical modeling of 2DSBs with draft tube is given in Tab. 1. It should be noted that not all of these variables are necessarily important for each operational phase of spouted beds.

The normal distance (W_o) of the orifice was calculated from relationship of separation distance (H_E) and slant angle (θ_s): $W_o = H_E \cos\theta_s$

Solids circulation rate: The relevant variables given in Tables 1-2 for the development of the model for the solids circulation rate (average particle velocity) were arranged:

$$F\,(V_p,\ U_f,\ \rho_f,\ \mu,\ g,\ d_p,\ \rho_p,\ \phi,\ E_v,\ W_o,\ D_s,\ \theta_s,\ L_b,\ D_i,\ H_t)=0 \tag{1}$$

Taking the considered variables in Eq. 1 and using the repeating variables, the following dimensionless numbers were developed:

$$\begin{gathered} F\,[V_p/(gW_o)^{0.5}, d_p/W_o,\ U_f^2/gW_o,\ \mu^2/g\rho_f 2W_o^3,\ \rho_p\text{-}\rho_f/\rho_f,\ \phi,\ E_v,\ L_b/W_o, \\ \theta_s,\ W_b/W_o,\ D_s/D_i,\ H_t/W_o]=0 \end{gathered} \tag{2}$$

The *PI* numbers given in Eq. 2 were transformed in to the following dimensionless numbers in Eq. 3:

$$V_p/(gW_o)^{0.5} = F[d_p/W_o,\ Fr,\ Ar,\ \rho_p\text{-}\rho_f/\rho_f,\ \phi,\ E_v, L_b/W_o,\ \theta_s,\ D_s/D_i,\ H_t/W_o]=0 \tag{3}$$

Where, *Fr* and *Ar* are Froude number and Archimedes number respectively. The theoretical solids circulation rate would then be Eq. 4:

$$S_p = \rho_b A_d V_p \tag{4}$$

Where, A_d is the cross-sectional area of the downcomers.
Or:

$$\begin{gathered} S_p/\rho_b A_d (gW_o)^{0.5} = \\ = F[d_p/W_o,\ Fr,\ Ar,\ \rho_p\text{-}\rho_f/\rho_f,\ \phi,\ E_v,\ L_b/W_o,\ \theta_s,\ D_s/D_i,\ H_t/W_o] = 0 \end{gathered} \tag{5}$$

Average cycle time: The relevant variables from Tab. 1, which may constitute the mathematical model of average cycle time, are shown:

$$F\,(t_c,\ S_p,\ M_p,\ d_p,\ \phi,\ W_o,\ \theta_s,\ H_b, W_d) = 0 \tag{6}$$

Taking the pertinent variables from Eq. 6 and using the variables in Tables 1-2 the following dimensionless *PI* numbers were generated:

$$F(t_c S_p/M_p,\ \phi,\ ,\ \theta_s,\ W_o/d_p,\ H_b/d_p,\ W_d/d_p) = 0 \tag{7}$$

The dimensionless numbers in Eq. 7 were transformed in to the following *DPs* to simplify the relationship for average cycle time as shown below:

$$t_c S_p/M_p = F(\phi,\ ,\ \theta_s,\ W_o/d_p,\ H_b/W_o,\ W_d/d_p) = 0 \tag{8}$$

Experimental methods and procedures: The spouted bed drier used for the study is represented in Fig. 1, it consists of motor-blower assembly, heating chamber, hot air delivery duct, temperature controller, plenum chamber and spouted bed chamber. The airflow rate could be adjusted using the built-in motor blower on the suction side. The temperature of the inlet hot air was controlled using temperature controllers. The system was also fitted with ball valves in between the hot air delivery duct and spouted bed to keep cardamom capsules in minimum spouting conditions for as long as needed by adjusting the airflow rate. The design of the two dimensional spouted bed provided the opportunity to vary the bed length-width, the slant angles, separation distance, spout width and air entry slots. A detailed description of the design and measurement procedure is provided in Part 1 of the study.

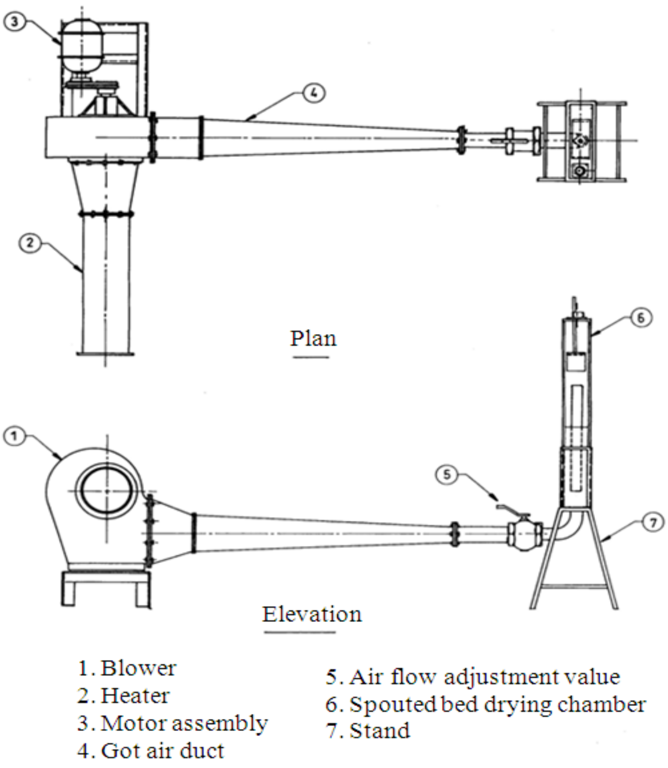


Figure 1. Schematic diagram of spouted bed dryer

RESULTS AND DISCUSSION

PI terms proposed for solids circulation rate and average cycle time were generated from the experimental data and linearized by natural logarithm transformation. M-STAT was used to analyze the data using full regression model and the model was evaluated on the basis of the R^2 statistic, standard error, level of significance (α), residual characteristics and the number of terms in the model.

Solids circulation rate/average particle velocity: The average particle velocities observed over all the runs were in the range of 0.76-1.25 cm·sec^{-1}. The lowest particle velocity was 0.76 cm·sec^{-1} in the case of cardamom dried at air temperature 40°C, 45° slant angle, 5 cm separation distance and draft tube height of 40 cm and the highest was 1.25 cm·sec^{-1} in the case of cardamom dried at air temperature 50°C, 60° slant angle, 7.5 cm separation distance and draft tube height of 60 cm with tempering period for 30 min. The solids circulation rates were calculated from the average particle velocity, the effective cross-sectional area of the down comers and the average bulk density. Plots of solids circulation rate versus draft tube heights for various slant angles and separation distances have been shown in Figs. 2-3. It may be observed that the solids circulation rate increased with separation distance. Possible cause for this trend as explained by Buchanan and Wilson (1965) [9], Khoe and Brakel (1983) [1] and Claflin and Fane (1984) [10] for Conical-cylindrical spouted beds and Law *et al.* (1984) [11] and Kalwar *et al.* (1992) [2] for two-dimensional spouted beds.

The solids circulation increased as the draft tube height increased from 40-60 cm and its magnitude increased with separation distance as shown in Figs. 2-3. The solids circulation rate was almost the same when the draft tube height was increased from 50-60 cm, but the difference became greater as the separation distance increased due to the higher number of capsules entering the draft tube.

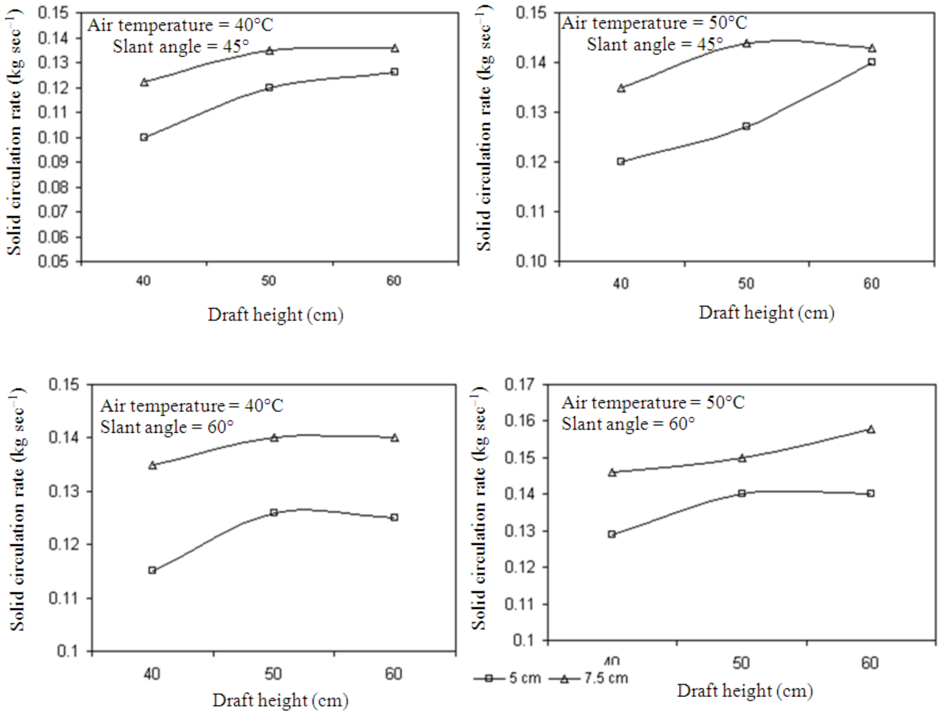


Figure 2. Effect of draft height (H_t) on solid circulation rate for cardamom

The effects of slant angle were detectable when the separation distances were 5 and 7.5 cm as can be judged from Figures 2-3. A steady increase was observed in solids circulation with a rise in slant angle from 45°-60°. This occurred because the solids circulation rate was limited by the dimensions of the orifice formed at the point of normal distance from the slanting base to the bottom of the draft tube. These dimensions decreased as slant angle increased at the same separation distance.

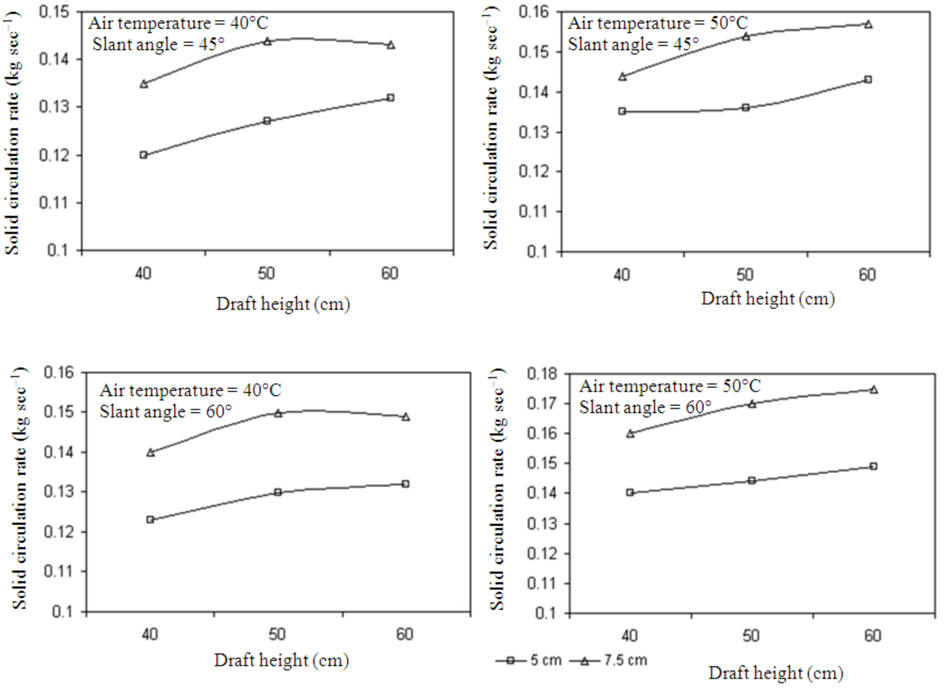


Figure 3. Effect of draft height (H_t) on solid circulation rate with tempering for 30 min for cardamom

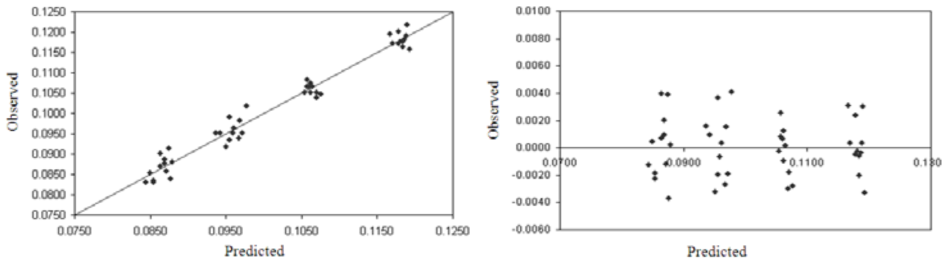
Hence, higher than minimum airflow through the bed will not enhance the solid circulation rate. Any further increase in slant angle decreased the solids circulation rate as well as air percolation into the down comer.

From Figs. 2 and 3, it was also observed that the increase in air temperature produced a positive effect on solids circulation rate. This was due to the fact that most of the heating of cardamom capsules occurs in the draft tube and the temperature of air increased the circulation rate of capsules. The mathematical model obtained for solids circulation rate is shown below:

$$S_p / P_b\, A_d\, (g\, W_o)^{0.5} = (U_f^2/g\, H_t)^{-0.2435}\, (d_p/Wo)^{6.5\,E\,-15}\, (L_b/W_o)^{0.5513}\, (D_s\, H_t/D_i\, W_o)^{0.0614}\, (\theta_s)^{0.6268} \qquad (9)$$

with R^2 = 96.51%, standard error of estimate = 0.0225 and α = 0.0001. A print out of residuals against selected model predictions is shown in Fig. 4b. The plot of observed and predicted values for the solids circulation rate model is plotted in Figure 4a. The developed model predicted the collected data with an average error of ±1.8%. The predictions from the solids circulation rate model have been presented in Fig. 4a, which showed a good agreement.

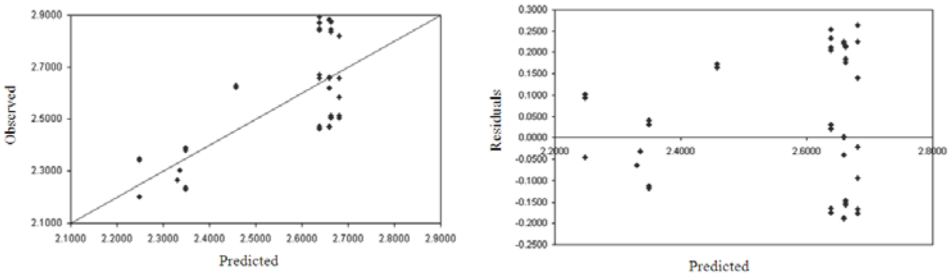
Average cycle time: The cycle times of particles in the case of 45° were 16-20% greater than the slant angle of 60° because of longer particle paths and the mass of grains in the bed. The shortest particle cycle time of 105 sec was observed when the slant angle was 60°, separation distance was 7.5 cm, draft tube height of 40 cm and air temperature of 50°C with tempering period of 30 min. The longest cycle time of 200 sec was found when slant angle was 45°, separation distance was 5 cm, draft tube height of 60 cm and air temperature of 40°C.



(a) (b)

Figure 4. (a) Comparison of solids circulation rate measured with solids circulation rate predicted by Eq. 9 (b) Residual plot for solids circulation rate model, Eq. 9

For any given geometry, the particle cycle time decreases with the distance of particles in the down comer.



(a) (b)

Figure 5. (a) Comparison of observed cycle time data Vs predicted cycle time by Eq. 10 (b) Residual plot average cycle time model, Eq. 10

The cycle time data from the drying runs were regressed against the dimensionless numbers. In principle, the average cycle time should be equal to the mass of particles in the bed divided by the solids circulation rate. But this was not so in the study. The problem could be due to the effect of separation distance on the cycle time distribution of individual particles. The mathematical model developed for average cycle time is given in Eq. 10.

$$t_c\, S_p \,/\, M_p = (d_p/W_o)^{\,0.9495}\, (H_b W_d/W_o d_p)^{\,-0.9975}\, (\theta_s)^{1.11} \tag{10}$$

with $R^2 = 81.63\%$, standard error of estimate = 0.0618 and significance level = 0.0001. The model predictions versus observed average cycle times are shown in Fig. 5a. It is concluded that the developed model fits the collected data with an average error of ±12%. A print out of residual against selected model predictions is shown in Fig. 5b.

CONCLUSIONS

In part 1 of the study we concluded that spouting pressure drop increases with an increase in separation distance and slant angle. It was also observed that increase in draft tube height led to an increase in spouting pressure drop. We also concluded that minimum spouting velocity increases as the separation distance and draft tube height increase and as the slant angle decreases. In Part 2 of the study it was observed that solid circulation rates (average particle velocity in the down comers) were also affected by separation distance, draft tube height, slant angle and vary with spouting velocity. The average particle times were found to vary with slant angle. Emperical models were developed for solids circulation rate and average cycle time and were found to be in close agreement with expeimental data.

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STEPENI AERODINAMIKE I PROTOKA ČVRSTE MATERIJE U ODVODNIM KANALIMA ZA SUŠENJE KARDAMOMA (2. deo)

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Sažetak: Za proučavanje pada pritiska u odvodnom kanalu, minimalne brzine odvođenja materijala, stepena cirkulacije čvrstog materijala i prosečnog vremena ciklusa korišćene su dvodimenzionalne jedinice odvodnih kanala sa fleksibilnim dimenzijama. Podaci su prikupljani variranjem ugla nagiba, visine pripremnog kanala, rastojanja pri separaciji i visine kanala. Analizirane su veličine koje utiču na pad pritiska u odvodnom kanalu i protok kroz kanal. Razvijene su empirijske zavisnosti korišćenjem simulacije i dimenzione analize. Razvijene zavisnosti su bile u skladu sa prikupljenim podacima. Rad je podeljen u dva dela pri čemu se prvi deo bavi analizom pada pritiska u odvodnom kanalu i minimalnom brzinom odvođenja a drugi deo stepenom protoka čvrste materije i prosečnim vremenom ciklusa.

Ključne reči: *Pad pritiska pri odvođenju materijala, minimalna brzina odvođenja, stepen protoka čvrste materije, prosečno vreme ciklusa, dimenziona analiza, Elettaria cardamomum, konično-cilindrični kanal za odvođenje (CSB), komore za konzervaciju, pravougaoni otvori*

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