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# INTERPARTICULAR FORCES IN POWDERY MATERIALS BEDS

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*În prezenta lucrare se identifică şi se realizează cuantificarea tipurilor de forte interparticulare existente în straturile de particule pulverulente de natură anorganică şi biomateriale. Pe baza modelelor dezvoltate în literatură, utilizând diferite materiale se obțin valori pentru principalele tipuri de forte identificate. Identificarea şi evaluarea cantitativă a forțelor interparticulare este utilă în estimarea parametrilor dinamici din cadrul procedeelor intensive de termo – procesare sau/şi de transformare chimică.*

*In this paper the types of interparticular forces existing in the powdery inorganic and bio - materials beds were identified and quantified. Based on the models developed in literature, using different materials (sand, ash, corn and wheat flour) values for the main identified interparticular forces were obtained . The interparticular forces identification and quantification are useful in dynamic parameters determination in the intensive procedures of thermo-processing and chemical reaction.*

**Keywords:** powdery materials, van der Waals interactions, capillary forces

## 1. Introduction

The present paper follows the study of phenomena which take place during the powdery materials processing. Powdery materials are raw materials in some domains of chemical industry, pharmaceutics and food industry. The powdery materials have a special behavior during: transportation, storing, processing. This behavior is determined by the interparticular forces action. These forces have different origins as a function of materials nature and studied system: forces determined by the small dimensions (van der Waals), forces determined by hydrogen bounds (capillary forces), electrostatic forces, cohesion forces determined by biochemical structure of materials etc. The study aim is related with the use of physical data measurements such as particle and bulk densities,

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particle size, wetting angle at particle moistening for the estimation of the forces which act between two or more adjoining particles from powdery beds.

### *Van der Waals forces*

The attraction or repulsion Van der Waals dispersion forces depend on molecular distance. An equilibrium permanently exists between attractive and repulsive forces [1]. If the molecular distance is large, only bipolar interactions were considered, because they have a large interaction domain and are frequent. The complete characterizing of Van der Waals interactions must take in consideration the quatrupol and multi-polar interactions, especially in cases when molecules don't have dipole moment.

Lennard-Jones (1937) has proposed an empirical expression for the average global interaction energy between solid particles, $E_{L-J}$, considering London theory [1]:

$$E_{L-J} = C_{ss}\left[-\frac{1}{r_i^6} + \frac{z_{ss}^6}{2r_i^{12}}\right] \tag{1}$$

where $C_{ss}$ is the Lenard-Jones constant; $r_i$ - the interaction radius; $z_{ss}$ – the distance between the implied species;

The interaction potential, $U_{ss,}$ between two identical solid particles was obtained from equation (1) by integration on the particle volume [1]:

$$U_{ss} = \frac{A \cdot d_m}{12 \cdot z_{ss}}\left[-1 + \frac{1}{420}\left(\frac{r_i}{z_{ss}}\right)^6\right] \tag{2}$$

where: A is Hamaker constant, $A = \pi^2 \cdot \rho_1 \cdot \rho_2 \cdot C_{ss}$, the solid particle is considered rigid and spherical of average diameter: $d_m = \frac{d_1 d_2}{d_1 + d_2}$, $\rho_{1,\,2}$ – particle density, $d_{1,2,}$ - particles diameter.

The attraction force between solid particles is calculated with the Hamaker relation [1]:

$$F = \frac{\partial}{\partial z}\left(U_{ss}\right) = \frac{A \cdot d_m}{12 \cdot z_{ss}{}^2} - \frac{6}{420} \cdot \frac{r_i^6}{z_{ss}^7} \tag{3}$$

### *Capillary forces*

If at molecular level, the important parameter was the interaction potential between two molecules with close shell, but strongly electronegative, at macromolecular level the parameters which characterize the liquid nature are important, considered like a molecular association and the molecular assembly velocity. The capillary forces can be considered an application at macromolecular level of hydrogen bound.

Ennis and collaborators (1975) consider a model to calculate the capillary coefficient, $Ca_{l-H} = \eta \cdot w/(\sigma \cdot l^3)$, calculated like ratio between drag force and superficial tension force average on the volume, in which $\eta$ - liquid viscosity, Pa s; w – liquid velocity, m/s; $\sigma$ - superficial tension, N/m; l – drag force action distance, m [2].

When the capillary coefficient, $Ca_{l-H}$, respects the condition $Ca_{l-H}>1$, the effect of liquid viscosity is a major factor in capillary forces evaluation. When $Ca_{l-H}<10^{-3}$ , the most important factor in capillary forces calculation is the superficial tension parameter [2].

This physical model of capillary forces neglects the liquid transportation between particles and fluid volume of liquid bridges between particles variation. The model is valid for liquids with small viscosity which allow to neglect the drag forces from liquid bridges. This drag forces must be smaller than the forces determined by superficial tension, but sufficiently high to keep the liquid film on the particle and not to allow its migration through the contact points between neighbour particles. These hypothesis are suitable for the lower liquid content between solid particles [3].

The maximum force between two particle developed in a liquid bridge is determined by two components:

- the adhesion force determined by the limit superficial force at the interface of three phases liquid – solid – air;
- the pressure difference in or out of the liquid bridge: [2]

$$F_{capillary} = \pi \cdot d_p \cdot \sigma \cdot \sin\phi \cdot \left[ \sin(\phi + \theta) + \frac{d_p}{4} \cdot \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \cdot \sin\phi \right] \tag{4}$$

where: $d_p$ – solid particle diameter, m; $\sigma$ - superficial tension, N/m; $\phi$ - moistening angle, degree; $\theta$ - contact angle, degree; $R_1$, $R_2$ – curvature radius of liquid – solid interface. The moistening angle and contact angle depend of liquid volume in liquid bridges

## 2. Experimental

The physical characterization of different materials consisted in the determination of solid particle properties such as: size distribution, density, $\rho_p$ the material bed properties, bulk density, $\rho_V$. The determination of material sizes was realized by material size analysis of selected materials. The chosen fractions were: 75 µm, 100 µm, 125 µm, 150 µm, 200 µm, 250 µm.

The density of each solid material (particle) and bulk density were determined by usual methods for solid particles [5] and the material size analysis was done using a sieving device.

## 3. Results and discussions

The different values for the particle density, of particles obtained from the same material, are explained by the different chemical / biochemical structural area.

*Table 1*

**Bulk (** $\rho_V$, in kg m$^{-3}$) **and particle** ( $\rho_V$, in kg m$^{-3}$) **densities according to particle sizes (**$d_p$, µm)

| No. crt. | Material | Material Property | Particle sizes, $d_p$, µm | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 250 | 200 | 150 | 125 | 100 | 75 |
| 1 | Sand | $\rho_v$, | 1340 | 1340 | 1340 | 1340 | 1340 | 1340 |
| 2 | | $\rho_p$ | 2217.4 | 2217.4 | 2217.4 | 2217.4 | 2217.4 | 2217.4 |
| 3 | Ash | $\rho_v$ | 435 | 425.7 | 419.2 | 414.3 | 411.5 | 346.6 |
| 4 | | $\rho_p$ | 2758.5 | 2346.2 | 2432.5 | 2715.3 | 2688.9 | 2515 |
| 5 | Corn flour | $\rho_v$ | 504 | 504 | 504 | 425 | 425 | 425 |
| 6 | | $\rho_p$ | 1052 | 1052 | 1052 | 967.3 | 967.3 | 967.3 |
| 7 | Wheat flour | $\rho_v$ | 504 | 498.3 | 498.3 | 522.9 | 522.9 | 478.4 |
| 8 | | $\rho_p$ | 729.9 | 799.9 | 799.9 | 875.2 | 875.2 | 712.7 |

Considering the van der Waals constant for solids $C_{SS} = 10^{-39}$ J m$^6$, the average action radius of van der Waals force, $r_{ss} = 3.5 \cdot 10^{-10}$ m and average distance between particle, $z = 2.23 \cdot 10^{-10}$ m [4] the values for attractive force and interaction potential shown in Fig. 1, based on the Hamaker theory, were obtained for different particle diameters shown in table 1.

The Fig. 1 shows the variation of attraction force and interaction potential in function of particle diameter. It can be observed that while the attraction force decreases with the particle diameter increases and the interaction potential increases. It can be observed that for smaller than 100 micrometer particles the van der Waals forces are significant. As the particle sizes increases as the influence of the attractive van der Waals forces decreases.

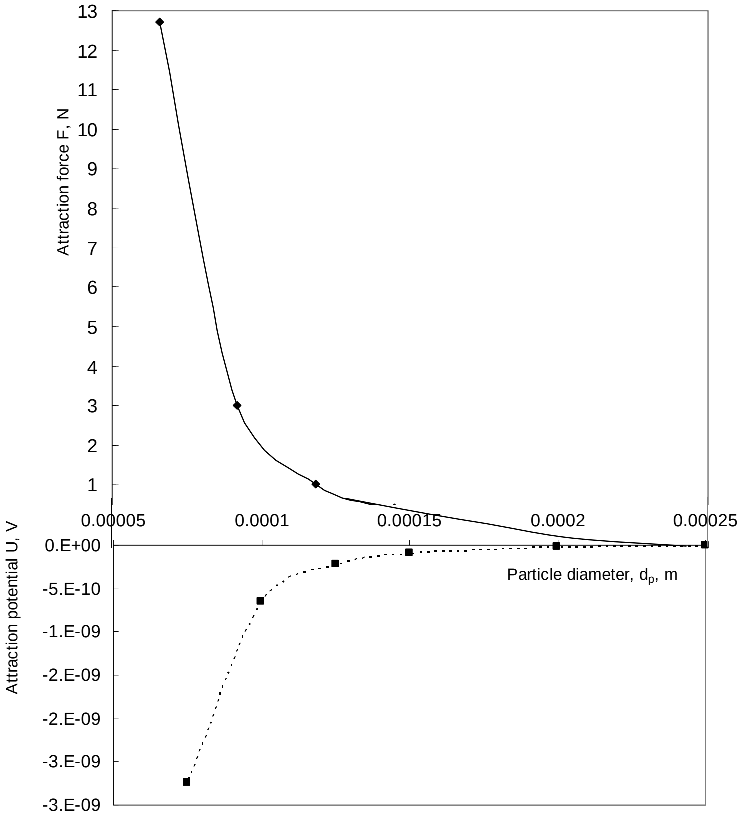

Fig.1. The attractive force and interaction potential variation function of particle diameter

For the repulsive force calculation the following relation was used [1]:

$$F_r = \frac{4}{3 \cdot K} \cdot \sqrt{d_m \cdot h_r} \tag{5}$$

where: $K = \frac{1-\nu^2}{Y}$, ν - Poisson coefficient; Y – Young elasticity modulus; $h_r$ – particle asperities height. Young modulus and Poisson coefficient were approximate from technical data reported for the studied materials.

Considering the asperity height of 1 Å, the following values shown in the Fig. 2 were obtained for the van der Waals repulsive force.

Comparing the values obtained for van der Waals attractive and repulsive forces is has been evidenced that in the established conditions the attractive interparticular forces are frequent at small particles. The attractive forces strongly increase with particle size decreasing, while the repulsive forces are smaller, but with a smooth increasing tendency with particle sizes decreasing (fig. 2).

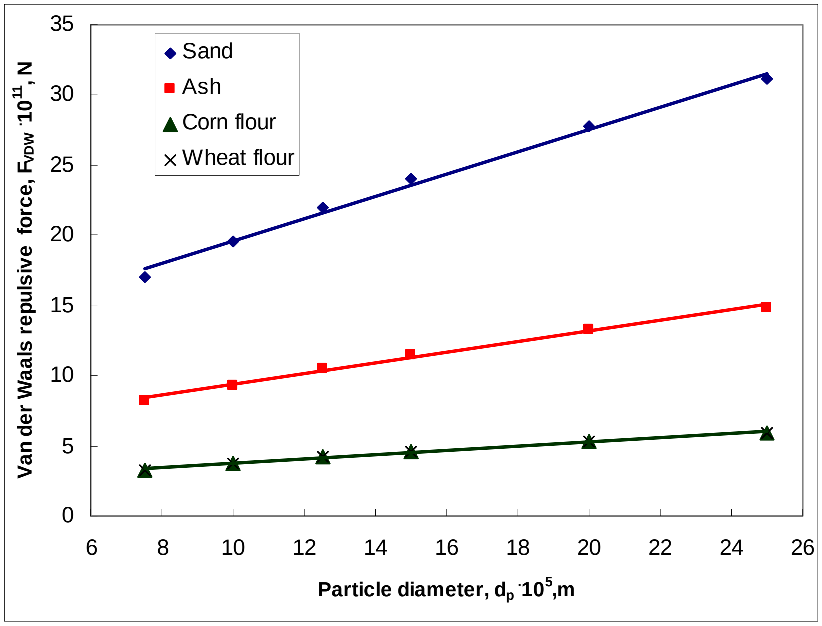

Fig.2. The van der Waals repulsive force function of particle diameter

The equations which describe the variation of van der Waals repulsive forces function of particle diameter for the studied materials were obtained from linear regression of experimental data. Those are given below, together with their correlation factor:

- sand:

$$F_{VdW} = 8 \cdot 10^{-7} \cdot d_p + 10^{-10}, \quad R^2 = 0.9967 \qquad (6)$$

- ash:

$$F_{VdW} = 4 \cdot 10^{-7} \cdot d_p + 5 \cdot 10^{-11}, \quad R^2 = 0.9974 \qquad (7)$$

- corn and wheat flour:

$$F_{VdW} = 2 \cdot 10^{-7} \cdot d_p + 2 \cdot 10^{-11},\ R^2 = 0.9966 \qquad (8)$$

The capillary forces were estimated using equation 4. The moistening angle, $\phi$, function of liquid volume was considered, according to the moisture content and particle size. For sand and ash, with the 6% equilibrium moisture, for corn and wheat flour, with 10% equilibrium moisture, the moistening angle was estimated until $90^o$. For a moisture of 14% the estimation was made with a range angle of $90^o - 120^o$. The contact angle $\theta$, is $0^o$ were the solid particle is completely wet on the surface.

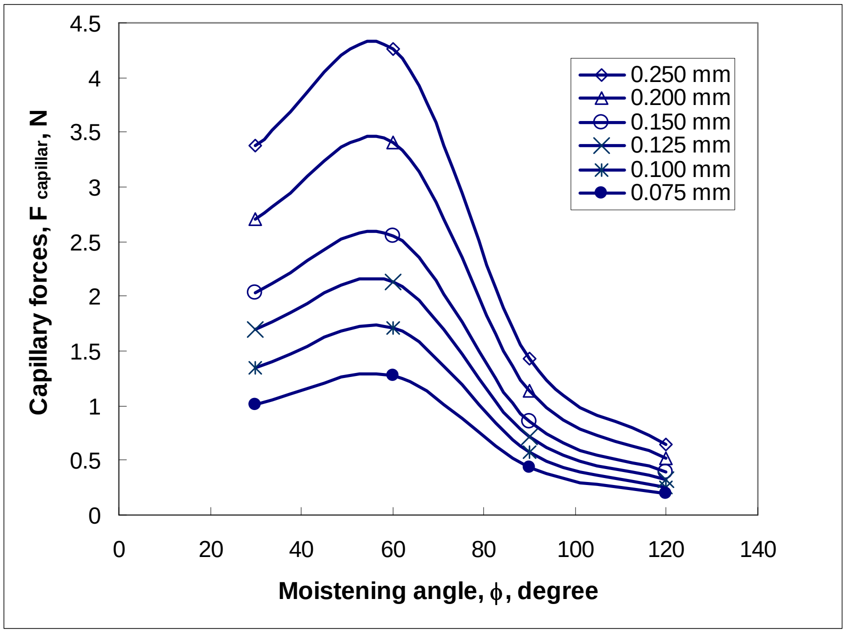

Fig. 3. Curves for capillary forces

One can observe from Fig. 3 that the capillary forces are important at moistening angle smaller than $90^o$, coresponding to moisture which doesn't determine the liquid saturation (smaller than 6% for sand and 10% for corn and wheat flour).

The presence of the maximum capillary forces can be explained by the theory of liquid bridges with concave forms of the meniscus giving stable liquid bridges (the pendular liquid bridges). In this type of bridges the attractive forces are dominant showing strong tendency of agglomeration. At small moistening angle (small moisture content of particle) the liquid bridges are instable because the liquid volume between the particles is insufficient.

At higher particle moisture content (moistening angle higher than $90^o$) the funiculate state is installed, the liquid fills all solid pores and the formed liquid bridge is convex and strongly repulsive forces appear.

## 4. Conclusions

The experimental research made in evidence and quantifies the interpaticular forces in the powdery inorganic and bio-materials beds. The cohesive character of the studied materials was justified by the presence of the van der Waals attractive and repulsive forces. The moisture content of the powdery materials beds (sand, ash, corn and wheat flour) induces the capillary force manifestation. The analysis presenting in the paper has studied the influence of the particle sizes and moistening degree, important for the identification of these forces; another important factor is the particle structure, which be ulterior analyzed.

Our study shown that the irregular forms and small sizes of inorganic materials (sand) are the main factors in the complex behavior of those materials at dynamic processing. Also for the biomaterials (corn and wheat flour) an important factor is chemical structure of the material, which determines certain morphology of the particle surface and a higher deformability character. For the materials with mix composition (ash) summarize all those properties and their behavior is mostly atypical.

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