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Tadeusz GLUBA*, Bogusław KOCHAŃSKI*

WATER PENETRATION INTO THE BED OF FINE-GRAINED MATERIALS

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Results of studies on water penetration into a model bed of glass balls 50 μm in diameter and three beds of silica flour with mean particle diameters 54, 24 and 17.7 μm are discussed in the paper. The tested silica flour beds had different values of standard deviation. In the tests a laminar macroscopic flow of liquid was analysed. It was found that geometry of a porous bed and properties of substances had an influence on the flow efficiency. With an increase of the bed height, water penetration rate into silica flour decreases, while for glass balls it increases. This provides evidence of structural changes in the bed during flow of water which covers particles with a liquid film and decreases friction coefficients, enabling displacement of fine particles in big voids, a decrease of porosity and an increase of flow resistance. The water penetration rate depends on particle size, wetted bed layer structure, bed height and porosity.

Key words: water penetration, porous bed, particle size

INTRODUCTION

The flow of liquid in porous beds accompanies many phenomena that occur both in nature and in production processes in many industrial branches. It is specially important in nature in the case of erosion of rocks and propagation of rainwater in soil, while in multi-phase production processes it is significant when comminuted solids with a high degree of dispersion occurring in the form of catalysts, substrates or products are used. It plays a significant role in the agglomerative granulation of powder substances, it determines the mechanism of binding and the rate of liquid supply, as well as the quality and structure of granulated product.

Experimental, theoretical and numerical studies of liquid flow in porous substances published so far, have not provided a clear, universal solution to the problem (Shavit et al. 2004; Bucs and Panfilov 2004). A reason may be its complexity. Solution for a

* Technical University of Łódź, Department of Process Equipment
90-924 Łódź, Stefanowskiego 12/16, Poland, e-mail: gluba@wipos.p.lodz.pl

system of complex geometry is the more difficult the bigger is the dispersion of particles in the bed (Hammecker et al. 2004). The amount of gas particles adsorbed in the pores on particle surface in the bed increases. The gas flow resistance in the interparticle space grows. An additional factor that makes the solution difficult is a changing structure of the bed whose particles are subjected to variable pressures (Bennethum and Weinstein 2004) of intermolecular forces on the interface. In the case when a new, not verified liquid–solid system is applied, inadequate knowledge of the problem may be a reason why separate experimental studies will have to be carried out.

A driving force of liquid penetration into the bed is the difference of pressures on the liquid front interface called suction pressure. On the interface, on the side of the gas phase a gas boundary sublayer can be separated and on the liquid side a boundary liquid sublayer can be found. In the case of a flat interfacial area, pressure in the two sublayers is the same. As a result of the contact of both phases with a solid phase, curvature of the boundary surface changes and a new relation between acting forces of the system is settled. When the capillary surface is well wetted, in the liquid concave sublayer of the boundary surface the pressure is lower than in the gas sublayer. A difference of these pressures called a bubble or capillary pressure, is defined by Laplace formula

$$\Delta P_{maks} = \frac{4(1-\varepsilon)}{d_k \varepsilon}\sigma \tag{1}$$

where: σ – liquid surface tension, Pam,
d_k – capillary diameter equal to two radii of meniscus curvature, m,
ε – porosity.

In the bed of granular material, the following formula is used for its determination

$$\Delta P_{\sigma} = \frac{6(1-\varepsilon)\sigma}{\varepsilon d_e} \tag{2}$$

where:
ΔP_{σ} – subatmospheric pressure under liquid surface, Pa
d_e – particle equivalent diameter, m.

A liquid element (Fig. 1) under the influence of a given system of forces, can displace along three directions of the spatial coordinate system axes.

In the upward flow of liquid along the z axis, the force of suction is opposed by the forces of resistance of flow and gravity force. A resultant force imparts acceleration to the liquid according to the relation:

$$\Delta P_{\sigma} - \Delta P_h - \Delta P_{st}^{G} - \Delta P_{st}^{C} = \frac{m}{A}\frac{dw}{dt} \tag{3}$$

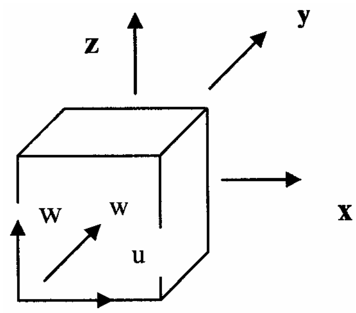

Fig. 1. Liquid element and velocity components in the spatial system of coordinate axis

where: $\Delta P_h = \rho g h$ – hydrostatic pressure of liquid, Pa,

$\Delta P_{st}^{C} = \zeta_c \dfrac{w^2}{2}\rho_c$ – pressure loss due to resistance of liquid flow in the bed, Pa,

$\Delta P_{st}^{G} = \zeta_g \dfrac{w^2}{2}\rho_g$ – pressure loss related to resistance of air flow in spaces unoccupied by liquid above its meniscus, Pa,

A – cross-section area of flowing liquid, m^2,

m – mass of liquid, kg.

Assuming isotropic bed properties in the whole cross section and complete filling of the interparticle spaces with liquid, the relations between the forces can be written in the form

$$\frac{6(1-\varepsilon)}{d}\sigma A - \varepsilon A \rho_g \zeta_g \frac{w^2}{2} - \varepsilon A \rho_c \zeta_c \frac{w^2}{2} - \varepsilon A h \rho_c g = \rho_c \varepsilon A h \frac{dw}{dt} \tag{4}$$

In the conditions of steady flow, liquid velocity is constant, w=const, and

$$\frac{dw}{dt} = 0 \tag{5}$$

Substitution of linear velocity by of mass flow rate Q

$$w = \frac{Q}{\rho_c A \varepsilon} \tag{6}$$

and taking (5) gives relation (7)

$$\frac{6(1-\varepsilon)}{d}\sigma A - \left(\zeta_g \rho_g + \zeta_c \rho_c\right)\frac{Q^2}{2\rho_c^2 A \varepsilon} - \varepsilon A h \rho_c g = 0 \tag{7}$$

which upon substitution of (6)

$$C = \frac{\zeta_g \rho_g + \zeta_c \rho_c}{\varepsilon A^2 \rho_c^2 2} \tag{8}$$

assumes the form:

$$\frac{6(1-\varepsilon)}{d}\sigma - CQ^2 - \varepsilon h \rho_c g = 0 \tag{9}$$

It enables determination of liquid penetration rate to the bed of fine-grained material

$$Q^2 = \frac{6(1-\varepsilon)}{Cd_e}\sigma - \frac{1}{C}\varepsilon h \rho_c g \tag{10}$$

Determination of supplied liquid rate (wetting rate) during granulation that is required to carry out the process, is a specially important problem. According to equation (10), it depends on particle size and structure of the wetted material layer determined by its thickness and porosity.

EXPERIMENTAL

To determine the rate of liquid front displacement in the bed of fine-grained material Dieragin's method was used (Aksielrud and Altszuler 1987). Figure 2 shows a schematic diagram of the measuring set-up. The set-up consists of a wetting chamber connected to the wetting liquid tank by means of a water lever. The chamber and tank form a system of connected vessels. The level of liquid in the wetting chamber corresponds to the level of wetting liquid in the tank. Inner diameter of the wetting chamber is not much bigger than the external diameter of exchangeable, measuring cylinders of different heights (10, 20, 30, 40, 50 mm). The measuring cylinders were made from a copper pipe. A perforated bottom of the cylinder made from brazen mesh, covered with filter paper, is a basis for granular material that fills completely the inside of the measuring vessel. After weighing the measuring vessel that contained a tested material sample, it was inserted into the wetting chamber. Loss of liquid in the tank is equal to the liquid increment in the bed. The process of liquid penetration to the bed of fine grained material is estimated by weight according to the measurement of liquid loss in the tank placed on an electronic weigher. Indications of the weigher recorded every two seconds were stored in a computer memory.

Properties and types of tested materials are given in Table 1. Figure 3 presents their particle size characteristics.

Distilled water at the temperature 20ºC was used in the experiments.

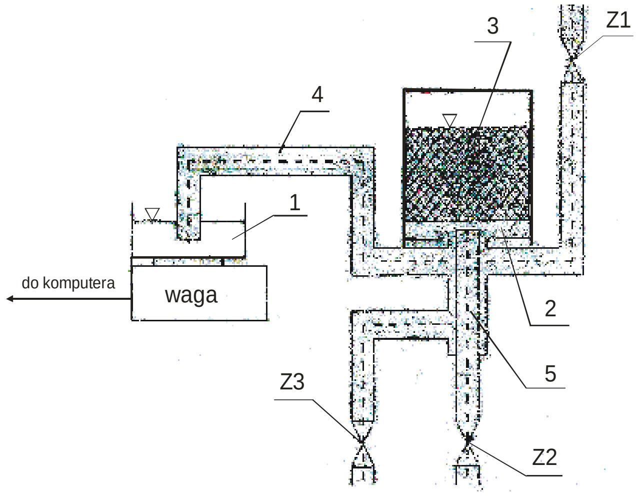

Fig. 2. Measuring set-up; 1 – liquid tank, 2 – wetting chamber, 3 – exchangeable measuring cylinder, 4 – pipe connecting liquid tank with the chamber, 5 – liquid control gauge in the chamber, z1, z2, z3 – ball valves

Table 1. Tested materials

Material	Symbol	ρ_s [kg/m^3]	s(d)[μm]	dś[μm]
Silica flour	Mk 100	2479	7	54
Silica flour	Mk 75	2257	7	24
Silica flour	Mk 56	2209	3.6	17.7
Glass balls	Ksz 50	2384	20	50

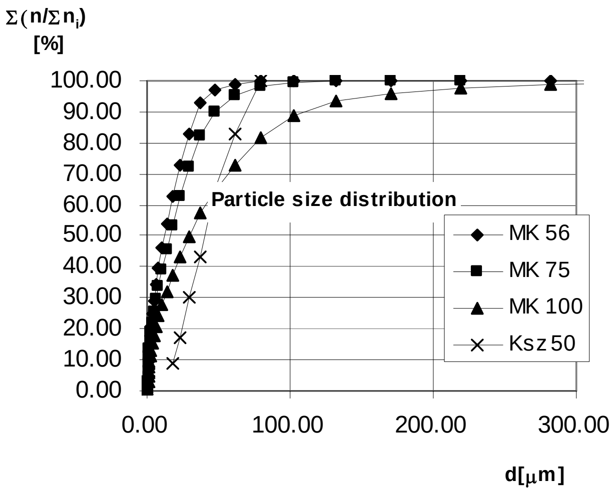

Fig. 3. Comparison of particle size distribution of the tested materials

RESULTS

Dependence of the amount of liquid which penetrates the bed on time, is a kinetic characteristic of the penetration process presented in the graphic form and is called the kinetic curve. Characteristics for particular beds of materials are shown in Figs. 4, 5, 6 and 7. Time is on the axes of abscissa, while the mass of sucked in water on the axis of ordinates. Subsequent curves correspond to the beds of different heights.

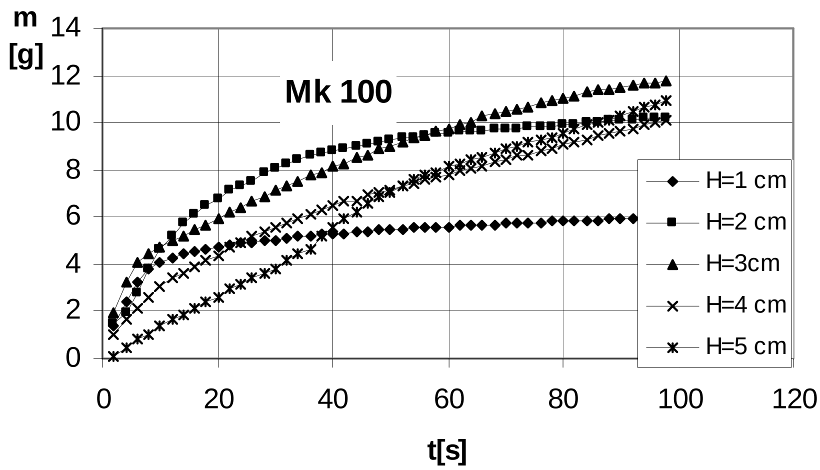

Fig. 4. Penetration curves for silica flour with mean particle diameter 54 μm

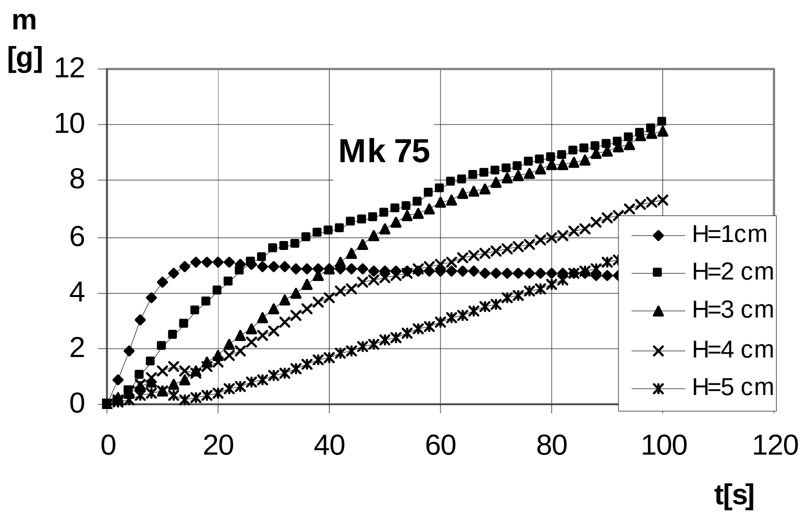

Fig. 5. Penetration curves for silica flour with mean particle diameter 24 μm

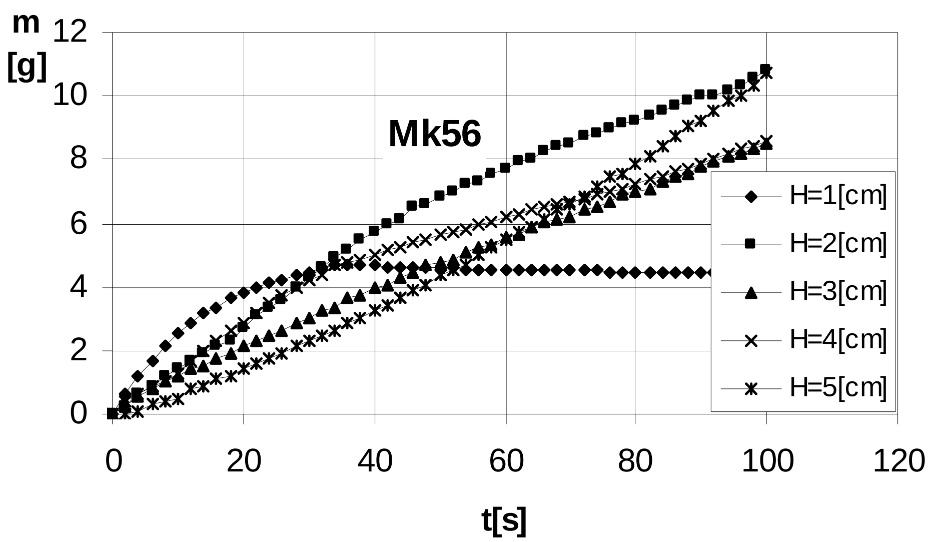

Fig. 6. Penetration curves for silica flour with mean particle diameter 17.7 μm

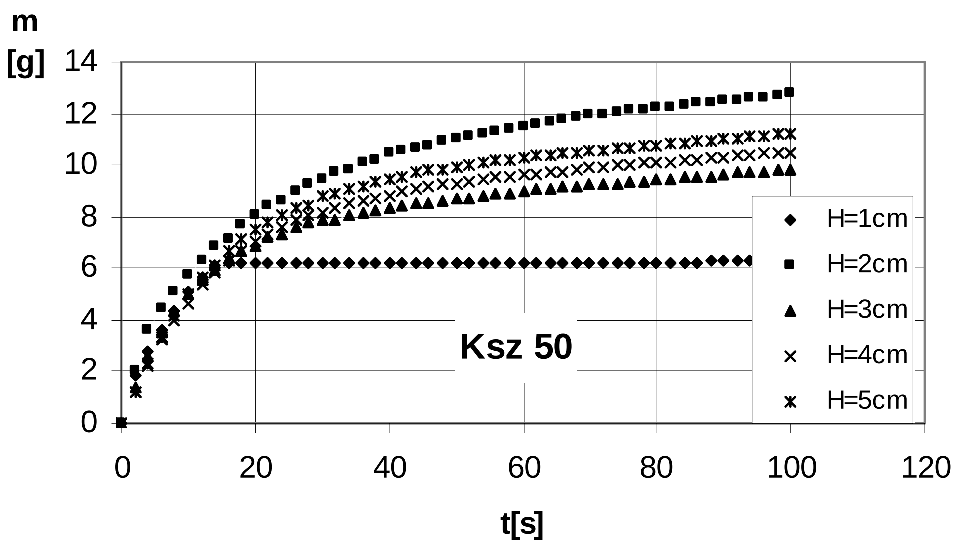

Fig. 7. Penetration curves for the bed of glass balls 50 μm in diameter

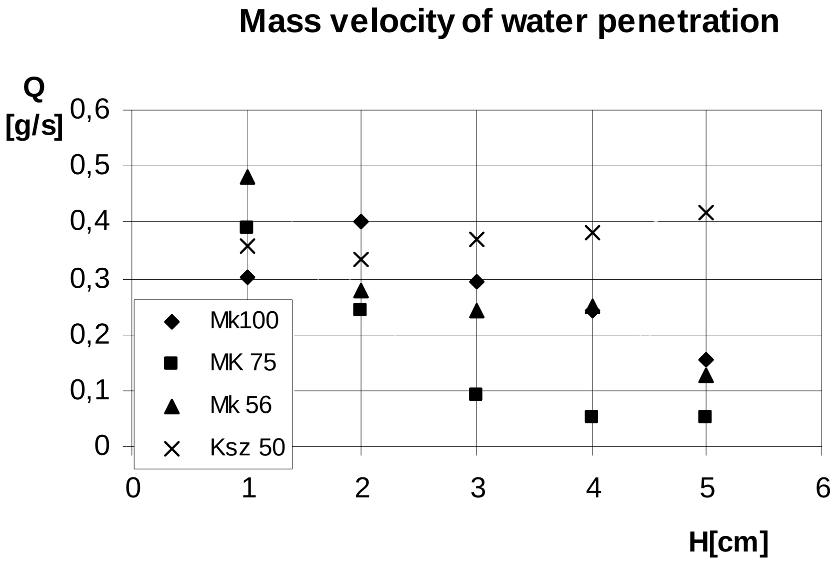

Fig. 8. The effect of tested material bed height on liquid mass penetration velocity

Table 2. Comparison of results obtained

	H=1cm	H=2cm	H=3cm	H=4cm	H=5cm	
Q [g/s]	0.30285	0.40296	0.29525	0.24321	0.1545	Mk100
Q_v [cm^3/s]	0.303	0.403	0.295	0.243	0.154	
w_o [cm/s]	0.02	0.027	0.02	0.016	0.01	
ε	0.708	0.639	0.5785	0.566	0.66	
w [cm/s]	0.028	0.042	0.035	0.028	0.016	
Q [g/s]	0.3879	0.2407	0.0923	0.0504	0.0523	MK75
Q_v [cm^3/s]	0.39	0.240	0.092	0.05	0.05	
w_o [cm/s]	0.026	0.016	0.006	0.0034	0.0034	
ε	0.571	0.555	0.558	0.552	0.555	
w [cm/s]	0.046	0.029	0.0108	0.0062.	0.0062	
Q [g/s]	0.4793	0.2796	0.2436	0.2511	0.1279	Mk56
Q_v [cm^3/s]	0.48	0.28	0.24	0.25	0.13	
w_o [cm/s]	0.032	0.019	0.016	0.017	0.00087	
ε	0.548	0.576	0.570	0.600	0.575	
w [cm/s]	0.058	0.033	0.028	0.028	0.0015	
Q [g/s]	0.358	0.3325	0.3685	0.38	0.4185	Ksz50
Q_v [cm^3/s]	0.12816	0.11056	0.13579	0.1444	0.1751	
w_o [cm/s]	0.024	0.023	0.024	0.025	0.028	
ε	0.4398	0.44	0.445	0.443	0.4464	
w [cm/s]	0.0546	0.0523	0.054	0.056	0.0627	

CONCLUSIONS

1) Based on the presented study, a macroscopic model of laminar liquid flow was proposed. According to the model, the properties of porous bed and substances (porosity, wettability) have an influence on the process efficiency, the height of rising and driving force.
2) The bed structure changes during liquid penetration. The changes depend on particle size distribution of material: for glass balls they were negligible and the biggest ones were observed for silica flour Mk100, a material with the biggest mean particle diameter.
3) In materials with the same particle size distribution, the bed with bigger mean particle diameter changed more significantly.
4) A comparison of water penetration rate of beds of different materials of similar mean particle diameter, silica flour – 54 μm (Mk100) and glass balls – 50 μm (Ksz50), indicates differences in the penetration process.
5) The proceeding bed consolidation during liquid flow is accompanied by elution of the finest particles, which are dislocated to the lower regions of the bed due to reduced friction in the wetted region. A consequence of this is a change of flow conditions.

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W pracy przedstawiono wyniki badań wnikania wody do modelowego złoża szklanych kulek o średnicy 50µm i trzech złóż mączki kwarcowej o średniej wielkości ziaren: 54, 24 i 17,7 µm. Badane złoża mączki kwarcowej różniły się wielkością odchylenia standardowego. Przeprowadzone badania pozwoliły na opracowanie makroskopowego przepływu cieczy w zakresie ruchu laminarnego. Stwierdzono, że geometria porowatego złoża i właściwości substancji wpływają na wydajność przepływu. Ze wzrostem wysokości złoża zmniejsza się tempo wnikania wody dla mączki kwarcowej natomiast rośnie dla złoża szklanych kulek. Świadczy to o zmianie struktury złoża w trakcie przepływu wody, która pokrywając ziarna ciekłym filmem zmniejsza wartość współczynników tarcia, umożliwia przemieszczanie się drobnych ziaren w dużych lukach, zmniejszenie porowatości oraz wzrost oporów przepływu. Tempo wnikania wody zależy od wielkości ziaren, struktury warstwy nawilżanego złoża, jego wysokości i porowatości.