Some Features of Pressure Evolution in Systems ”Non-Wetting Liquid – Nanoporous Medium” at Impact Intrusion

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Abstract. The last few decades systems consisting of nanoporous medium dispersed in a non-wetting liquid cause an increased interest from both the practical and theoretical points of view. Non-wetting liquid can infiltrate into the porous medium only with an excess pressure. Liquid infiltration tends to increase the solid-liquid interfacial energy and the absorbed energy is proportional to the specific surface area of the medium. Therefore this energy for nanoporous media can reach several orders of magnitude superior to traditional damping materials and shape-memory materials. As a consequence, the prospects of using devices based on systems consisting of a nanoporous medium immersed in a non-wetting liquid associated mainly with the absorption of mechanical energy of impact or explosion. The paper presents the results of experimental studies of impact intrusion the systems of industrially produced hydrophobic silicas Fluka 100 C8 and Fluka 100 C18 with distilled water. With increasing the impact energies nontrivial pattern of pressure changes in the system over time is observed.

1. Introduction
For dispersing the non-wetting liquid into the system of liquid clusters in the pores of the nanoporous disordered medium external pressure must be applied. Depending on the rate of growth external pressure [1] two different scenarios are possible to fill the pores with liquid. Wherein physics infiltration process at high speeds the pressure is significantly different from infiltration at low speeds. Most modern experimental and theoretical study of such systems is related to the quasi-static regime with the infiltration rate of the pressure of not more than \( \dot{p} < 10 \text{ atm/s} \). At such speed it was found a number of effects, such as a dispersion transition [2] and anomalously slow relaxation [3]. These effects open up a range of opportunities for different applications: sensors, passive protection systems with controlled release of substances such as drugs with changes in temperature, the passive fire protection systems in creating smart materials with controllable permeability for liquids or gases.

At impact or explosion a rapid growth of pressure is occurred in system with rates of \( \dot{p} = 10^4 \div 10^5 \text{ atm/s} \). The prospects of using devices based on systems consisting of a nanoporous medium immersed in a non-wetting liquid associated mainly with the absorption of mechanical energy of impact or explosion. Liquid infiltration tends to increase the solid-liquid interfacial energy and thus the absorbed energy can be estimated as \( E \sim \Delta \gamma S \), where \( \Delta \gamma \) is a solid-liquid interfacial tension, and \( S \) is the specific surface area of the medium. Therefore this
energy for nanoporous media can reach several orders of magnitude superior to traditional damping materials and shape-memory materials [4, 5]. Particularly there are considered the development of automotive dampers [6], the system of protection against strains and by the earthquake [7]. To the theoretical study of the processes by rapid intrusion, including modeling, devoted not so much articles [1, 8–10]. In [8] shows that the observable system can absorb more energy density in comparison with the case of quasi-static pressure. A lot of papers [6] are devoted to experimentally investigation of the development of car damper. Despite this, a set of experimental data is presented rather poorly and full-fledged studies are missing.

2. Experiment

In the present study we investigated the dynamics of non-wetting liquid during water infiltration into commercially available silica gels with a random structure of pores obtained in the sol-gel process Fluka 100 C8 — Silica gel 100 C8, Reversed phase (Sigma-Aldrich catalogue 60755) and Fluka 100 C18 — Silica gel 100 C18, Reversed phase (Sigma-Aldrich catalogue 60756-50G). Using the pycnometry (micro-Ultrapyc 1200e, Quantachrome Instruments) and porometry (Nova 1200e, Quantachrome Instruments) methods, we determined the density ($\rho$), specific surface area ($S_p$), specific volume of pores ($V_p$), and pore size distribution by the classical Barrett-Joyner-Halenda (BJH) method within the cylindrical model of pores and porosity ($\varphi$) of this material. The results are presented in Table 1.

A 4 g sample of the nanoporous medium was placed in a liquid-permeable container in the pressure chamber with volume of $\sim 60$ cm$^3$ (Fig. 1). The chamber was filled with distilled water. A falling weight from certain height is designed to impart a load pulse. Impact energy is determined by the variation of height. The direct method of measurement is described in detail at [1].

![Figure 1. The pressure chamber: 1 cell; 2 plug; 3, 6 gaskets; 4 screw top; 5 stock; 7 nanoporous medium; 8 membrane; 9 non-wetting liquid (water)](image)

The typical results of experimental measurements of pressure versus time with nanoporous media are shown in Fig. 2, 3, the range of variation of energy ranged from 10 to 60 J.
Table 1. Characteristics of the studied porous media.

|       | Fluka 100 C8 | Fluka 100 C18 |
|-------|--------------|---------------|
| $\bar{R}$, nm | 3.9 ± 0.2    | 3.9 ± 0.2     |
| $\rho$, g/cm$^3$ | 1.7603 ± 0.0034 | 1.6125 ± 0.0025 |
| $V_p$, cm$^3$/g | 0.56 ± 0.02   | 0.46 ± 0.02   |
| $S_p$, m$^2$/g (BET) | 267 ± 10     | 183 ± 6       |
| $\varphi = V_p/(V_p + 1/\rho)$ | 0.49 ± 0.02   | 0.42 ± 0.02   |

Figure 2. The dependence on the time of pressure change in the system "nanoporous medium – non-wetting liquid" for Fluka 100 C8 – water at different impact energies

Figure 3. The dependence on the time of pressure change in the system "nanoporous medium – non-wetting liquid" for Fluka 100 C18 – water at different impact energies

3. Results and discussion
Evolution of pressure occurs in several stages and depends essentially on the energy of impact. If the energy is not enough to overcome the pressure threshold at impact intrusion $p_0$, then there
is an elastic compression of the entire system without filling pores of a porous medium. For the systems "granular porous medium Silohrom CX 1.5 – Wood’s alloy”, ”Libersorb 23(C8) – water” and ”Fluka 100 – water”, it was found that infiltration occurs at the percolation threshold at a pressure far above the threshold pressure at quasi-static mode $p_{c0}$ [1]. So far the first system pressure threshold value of $p_0 = 1.6 p_{c0}$ [1], and for the third — $p_0 = 2 p_{c0}$ [8]. If the energy is such that the pressure exceeds the value of $p_0$, then before system achieve this pressure also elastic compression occurs, which is then followed by the filling of pores by non-wetting liquid. In this case intrusion is occurred at constant pressure. These experiments (Fig. 2, 3) shows that at the energy of 10 J pressure is enough to the beginning of filling at impact intrusion. At higher energies, where the energy of compression exceeds the maximum value determined by the energy density of the porous medium filling and intrusion mode at constant pressure is not realized. In these circumstances a response of system non-wetting liquids – nanoporous medium is elastic deformation due to the filling of the porous medium is not provided the necessary speed of energy absorption and characteristic pressure growth time. This case is accompanied at the end of filling increase of pressure to a maximum and then only outflow.

A intrusion pressure dependence on the impact energy of the investigated porous media is presented in Fig. 4. Data are also presented for the maximum pressure. From these data it follows that the intrusion pressure changes slowly with a slight tendency to increase. Lastly, maximal pressure for Fluka 100 C18 grows two times.

![Figure 4. The intrusion pressure and maximum pressure dependences on energy in the system "nanoporous medium – non-wetting liquid"](image)

Another feature of pressure evolution is the presence of oscillations. Such oscillations have been observed previously for the systems "Silohrom CX 1.5 – Wood’s alloy” and ”Libersorb 23 (C8) – water” [1,12] in the range of energy, where a constant pressure is occurred. However, the reason why they are not observed in the studied systems in this paper remains open and requires a separate study.

Thus, the magnitude of the change in volume of the system within the measurement error coincides with a change in volume due to deformation, and this means that there is no filling of the porous medium at low impact energies. With increasing impact energy is observed infiltration to the porous medium with a pronounced plateau in the pressure versus time. At higher energies intrusion mode at constant pressure is not realized due to the filling of the porous medium is not provided the necessary speed energy absorption. The response of system non-wetting liquids – nanoporous medium in this case is elastic deformation.
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