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Research paper

# Response of a nanofluid system based on a porous medium to an impact loading

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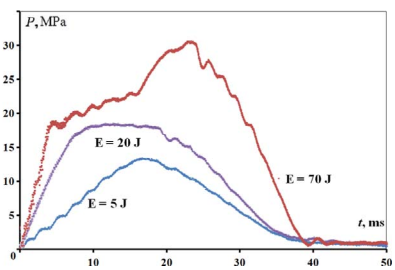
## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

New results are presented for the response of three nanofluid systems to an impact loading. It has been shown that the main criteria of the efficiency of such systems are the force and time of loading on a protected object, as well as the fraction of the impact/blast energy absorbed by such a system. The efficiency of energy and momentum absorption in the performed experiments was ~74–98%. Conditions have been determined under which the efficiency of energy and momentum absorption increases with the impact energy. The performed studies for three different systems have indicated that these conditions are universal. It has been shown on the example of these systems that the use of a «nanoporous medium–nonwetting liquid» system as the main element of devices for impact/blast mitigation makes it possible to control the loading force on the protected object (to ensure the loading force always below the allowed level) and to hold a high energy capacity.

## 1. Introduction

The properties of energy dissipation at irreversible deformation of various materials such as metals, composites based on high-strength fibers (aramid, etc.), polymers, ceramic materials, various foams, materials with cellular and layered structures are used to develop devices for protection from impacts and blasts (see, e.g., [1–11]). The focus of studies concerning the search for effective media for impact/blast energy absorption has been recently shifted toward potentially more energy capacitive materials with characteristic nanoelements [12,13]. Representatives of these materials are nanoporous media [13] with a pore size of 1–100 nm and nanofluid systems consisting of a nonwetting liquid and a nanoporous medium [13–17]. It was proposed to use buckling carbon nanotubes [10] and three-dimensional metallic microlattices [1].

The idea of using nanoporous media is based on the energy absorption in the process of deformation, which is accompanied by the collapse of nanopores or by a decrease in their volume. The absorption energy capacity of the medium at the deformation of pores incompletely filled with the liquid in the nanoporous medium at the

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quasistatic increase in the pressure was studied in [13] for disordered $SiO_2$ silica gel in a ductile state. The authors of [18] studied energy absorption at the deformation of a number of metal–organic frameworks (MOFs) at their transition from a large-pore state to a small-pore state. It was found that the viscoplastic deformation of nanoporous $SiO_2$ occurs at a threshold pressure of 650 MPa, and the transition in MOFs occurs at ~ 160 MPa. The relative change in the volume in these transitions is 30 and 40%, respectively. The specific absorbed energy at such pressures and changes in the pore volume can reach 300 J/g.

In spite of difference in the processes of impact and blast energy absorption, a common problem is to limit either the force or the momentum acting on a support (on a protected object). In the case of using energy dissipation at the plastic or viscoelastic deformation of a nanoporous medium, as well as at irreversible deformation of high-strength materials, a high specific energy capacity at the same deformation volume is reached owing to a high pressure at which deformation occurs. However, the force acting on the support (on the protected object) is large at a high pressure. This complicates providing the conditions for limiting the force or momentum transfer action. The problem of limiting the loading force (momentum) at a high energy capacity can be possibly ensured by using a nanofluid system consisting of a nonwetting liquid and a nanoporous medium in impact (blast) mitigation devices. This system provides an additional possibility of reducing the loading force (momentum) owing to the filling of nanopores with the nonwetting liquid. The nonwetting liquid fills pores only at an excess pressure of $10^4$ to $10^8$ Pa depending on the liquid and porous medium. The energy capacity of such a nanofluid system is determined by a high specific surface of nanoporous media reaching $10^3$ $m^2/g$ and can be as high as ~ 100 J/g. These properties of the system make it possible to provide the conditions for limiting the loading force (momentum) on the support. Consequently, this system is promising for the application in various devices for the absorption (mitigation) of impacts and blasts with various durations.

The process of impact/blast energy absorption by various systems consisting of a nonwetting liquid and a nanoporous medium has been studied in recent years at various relations between the characteristic times of varying the volume and pressure [14,19–21]. The experiments reported in [14,19–21] showed that the reduction of the characteristic times of varying the pressure, $\tau_p$, and volume, $\tau_v$, near quasistatic filling increases the filling pressure. This result was obtained for $\tau_p \sim \tau_v \sim 1$–10 s at a filling rate up to 0.5 $cm^3/s$. According to studies [22–28] of the filling of nanoporous media (Fluka 100 C8, CNT et al.) with nonwetting liquids (water, glycerol, glycol, solutions) with various viscosities at various filling rates, this dependence is due to an increase in losses on viscous friction taking into account sliding on pore walls at an increase in the velocity of flow of the nonwetting liquid in nanopores. Such an increase in the filling pressure leads to an increase in the loading force on the protected object at an increase in the filling rate.

The authors of [20,22,26] studied the mitigation of a shock-induced elastic compression wave with a duration of 0.3 ms by the system consisting of the nonwetting liquid (water, LiCl solution) and the nanoporous medium (Fluka 100 C8).

The experiments were performed on a facility with the liquid and porous medium placed in a chamber between two long steel bars (fixed [20,22] or free [26]) and an impact acted on the first bar. This method is known as the split Hopkinson pressure bar (SHPB) technique [26]. The measurements of mechanical stresses in the compression wave show that an increase in the impact energy is accompanied by an increase in the ratio of the stress in the second bar to the stress in the first bar; i.e., the mitigation of the transmitted wave is worsened. However, an increase in the mass of the granular porous medium leads to a decrease in this ratio by an order of magnitude; i.e., mitigation is improved. The authors of [22] performed SHPB experiments with a LiCl aqueous solution and a nanoporous silica gel, which is a porous medium with similar properties where the surface of pores was modified as in [26] by alkylsilane for ensuring hydrophobic properties. Additional experiments were performed in [22] with this porous medium where the modified layer on the surface of pores was removed by heating. In this case, the porous medium became hydrophilic. This means that it is spontaneously filled with water. The mitigation of the elastic compression wave with a duration of ~ 0.3 ms was not observed in experiments with this hydrophilic medium.

The mitigation of the blast wave with an action duration of ~ 3 ms was observed for the system consisting of water and zeolite as a porous medium with the specific volume of pores $V_{por} = 0.24$ $cm^3/g$ and the specific surface $S = 700$ $m^2/g$ [19]. In those experiments, the porous medium in the form of granules with a diameter of 10–30 μm was compressed into a disk tablet. The tablet together with the liquid was placed in a soft polypropylene shell glued to an aluminum platform. A transducer for measuring the mechanical stress momentum in the transmitted wave was attached on the opposite side of the platform. The authors found the fivefold mitigation of the incident blast wave in the system under study. It is remarkable that wave energy absorption was observed at a low excess pressure of 0.035 MPa. This effect of blast wave mitigation was attributed to the filling of nanopores in granules with the liquid (nanofluidic energy capture). At the same time, it is noteworthy that the time dependence of the volume of the system including the liquid and the tablet made of porous granules was not recorded in the experiments. This dependence could justify such a conclusion.

The results of studying impact mitigation were first reported in [15,21]. It was found experimentally that, at an increase in the external pressure during an impact with a duration of ~ 10 ms and an energy up to 100 J, the pressure in the two studied systems consisting of (i) Wood's alloy and silochrome (SCh-1.5) medium and (ii) the $CaCl_2$ aqueous solution and Libersorb 23 (L23) increases, reaches a critical value of $p_0$, and then remains constant during the entire impact mitigation time. Impact mitigation occurs at a constant average pressure $p_0$ and at irregular oscillations of the pressure during the entire time of filling of pores in the porous medium. The $p_0$ values for both systems are higher than the corresponding quasistatic filling pressure. At an increase in the energy (momentum) of the impact, this constant pressure does not vary within the experimental error and only the impact energy absorption time increases. Thus, the test of the studied system indicates that impact mitigation is improved at an increase in the impact energy. In this property, the system under study and the conditions of impact mitigation differs from the systems studied in [29,30]. In the experiments reported in [21], the momentum transferred to the support can be reduced by an order of magnitude. As was found in [21], the time of response of the system to the impact is independent of the viscosity of the liquid, and, according to [35], the heat release in the filling–leakage cycle is much smaller than the impact energy because of the double difference effect.

A different picture under similar conditions was observed in [29,30]. The authors of [30] established that, at an impact with a duration up to 20 ms and an energy up to 400 J, the pressure in the system consisting of LiCl aqueous solution and zeolite β increases during the impact and passes through a maximum. The maximum pressure depends on the ratio of masses of zeolite and solution, the concentration of salt solution, and the zeolite pretreatment temperature. The temperature dependence of the volume of the system was not determined in that work. In [29], it was established that the volume dependence of the pressure in the (NaCl aqueous solution–nanoporous silica SP-1000-20, Daiso Inc.) system at impact loading with an energy of ~ 1 J and a duration of ~ 4 ms coincides with the dependence $p(V)$ in a quasistatic regime. This effect was observed when hydrophobic porous granules form a «condensate» (marble) with the confined NaCl solution. In the case of layered liquid–granule configuration of the system, $P(V)$ dependences are different in the quasistatic and dynamic impact regimes. In this case, the volume of filled pores is smaller than that in the case of the condensate with the confined solution.

The above results on impact and blast wave mitigation give a