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MODELLING A PARTIALLY LIQUID-FILLED PARTICLE DAMPER USING COUPLED LAGRANGIAN METHODS

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Abstract. Energy dissipation in particle dampers (PDs) is complex and occurs mainly due to the relative motion between particles and to their surroundings. The degree of relative motion is particularly sensitive to changes in the external vibration amplitudes. Low vibration amplitudes lower the relative motion between solid particles, and thus lead to significantly lower energy dissipation rates. In order to influence the degree of relative motion between solid particles, a method is investigated in which the PD is filled with a combination of solid and liquid fillings. Moreover, with the PD partially filled with a liquid, the solid particle shape plays a more profound role in enhancing the damping performance. In order to investigate the effects of complex particle shapes and an added liquid, a simulation model based on Lagrangian methods is presented in this work. In order to validate the simulation models, experiments were also carried out. The experimental setup consists of a PD mounted on a vertical leaf spring. The PD is a cylindrical container filled with complex shaped particles in combination with a liquid. The complex shapes, here chosen to be tetrapods, were manufactured using a Stereolithography 3D printer. A good agreement between simulations and experiments is observed. In order to gain a deeper insight, a numerical study is presented which investigates the effects of solid-liquid ratio on the dissipated kinetic energy.

1 INTRODUCTION

Particle dampers (PDs) are becoming a popular alternative to conventional dampers due to their relatively simple design and their flexible ability to dissipate energy over wide excitation frequencies [1]. A detailed review on PDs can be found in [2]. One of the main drawbacks of a conventional PD is, that it is highly sensitive to a change in vibration amplitudes. Especially, their damping performance reduces by a substantial amount under low forcing conditions [3]. One particularly promising idea to overcome such shortcomings is to partially fill the conventional PD with a liquid [4, 5]. The added liquid sloshes along with the solid particles which act as dynamic barriers, in turn dissipating significant amounts of kinetic energy. This dissipative effect due to liquid sloshing through barriers can be further enhanced by replacing the conventional spherical shapes, which were used in [4], with complex shapes, in this work tetrapod shapes. The tetrapod shape has been popularly used in coastal engineering applications as wave breaker to dissipate energy carried by powerful waves and thereby reducing coastal erosion [6].

In order to gain deeper insights into the influence of various parameters on the dissipated energy, a model of the partially liquid-filled PD based on Lagrangian methods is investigated. The solid particle interactions involving non-convex particle shapes are modelled using the Discrete Element Method (DEM). The fluid motion is modelled using the Smoothed Particle Hydrodynamics (SPH) method. A coupled SPH-DEM approach according to [7] is used to model fluid-solid interactions. The focus of this paper lies in showing that fully resolved coupled SPH-DEM simulations can be used to reliably predict solid particle shape effects on the dissipated energy in partially liquid-filled PDs.

This paper is structured as follows. In Section 2 a short description of the experimental setup is given. In Section 3 details about the simulation model are outlined. Then, in Section 4 simulation results are compared against experiments. Section 5 showcases a numerical study to investigate the effect of solid-liquid fill ratio on the PD performance. Finally, in Section 6 some concluding remarks are provided.

2 EXPERIMENTAL SETUP

In order to better understand the simulation results and to build confidence in the simulation model, hardware experiments were conducted. The experimental apparatus, which is identical to the one used in [4, 5] except for the filling, consists of a vertically mounted steel leaf-spring (480 mm $\times$ 30 mm $\times$ 3 mm) on top of which a particle damper is rigidly mounted. The PD is a transparent acrylic cylindrical container of a fixed inner diameter of 44 mm and an adjustable length of L. Using an electromagnet, the vertical leaf-spring with the PD mounted on it's top is given an initial displacement, released from rest and allowed to oscillate freely in its fundamental mode. A PSV500 Polytec Laser Doppler Vibrometer is used to measure the displacement and velocity of the PD container. Depending on various PD parameters such as solid-liquid fill ratio, solid particle shape, amount of liquid among others, different damping performance is achieved.

The solid particles used in the experiments were manufactured on a Formlabs Form 2.0 Stereolithography (SLA) 3D printer, using a resolution of 100 μm and a Photopolymer resin ("Black Resin", Formlabs Inc.). In order to prevent wrapping of the solid particles, extra support structures are automatically added during the printing process. After the printing, the printed parts go through a 3-step finishing process. First, the parts are removed from the 3D-printer platform. The removed parts are then washed in Isopropyl alcohol in order to dissolve any leftover liquid resin. Finally, the support structures are removed to obtain the solid particles. An overview illustrating the 3D-printing procedure is shown in Figure 1.

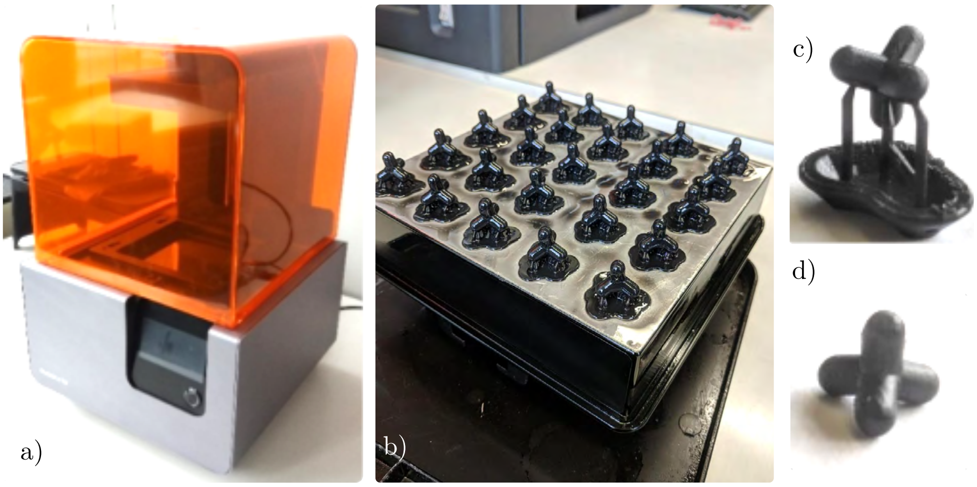

Figure 1: Non-convex polyhedron shapes manufactured using a 3D-printer. a) Formlabs Form 2.0 SLA 3D-printer. b) Multiple particles after 3D printing. A single tetrapod shaped particle c) before and d) after removing the support structure.

3 SIMULATION MODEL

3.1 Smoothed Particle Hydrodynamics

The Reynolds-averaged Navier-Stokes equations (RANS) are used to describe the fluid motion. The conservation of mass of the fluid with the Reynolds averaged velocity $\bar{\mathbf{v}}$ is given by

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho \nabla \cdot \bar{\mathbf{v}} \tag{1}$$

and the conservation of linear momentum is given by

$$\rho\left(\frac{\mathrm{d}\bar{\mathbf{v}}}{\mathrm{d}t}\right) = -\nabla \bar{p} + \mu \nabla^2 \bar{\mathbf{v}} - \nabla \mathbf{R} + \mathbf{f} \tag{2}$$

with density ρ, viscosity μ, Reynolds turbulence stresses $\mathbf{R}$ and external body forces $\mathbf{f}$. Here $\bar{p}$ is the Reynolds-averaged pressure. In this work, the weakly compressible Smoothed Particle Hydrodynamics (SPH) method is used to discretize the RANS equations according to [8]. In essence, the first two terms in Eq. 2, namely the pressure term $\nabla \bar{p}$ and the viscosity term $\mu \nabla^2 \bar{\mathbf{v}}$, are computed as proposed in [9]. An artificial stress term according to [10] and an artificial viscosity term as proposed in [11] are introduced in Eq. 2 to reduce the tensile instability and to smooth spurious numerical oscillations, respectively. In addition to this, a diffusive term is introduced in Eq. 1 to obtain smoother density fields according to [12]. Since the PD is only partially filled with a liquid, violent sloshing and large free surface deformations are expected. Therefore, an adequate modelling of turbulence is essential. In this work, the popular k-ε turbulence model according to [8] is used. Concerning the interaction between liquid and PD container, a penalty approach similar to the one described in [13] is used.

3.2 Discrete Element Method

The contacts between solid particles and PD container is modelled using the Discrete Element Method (DEM). The equations of motion of a single solid particle i is given by the Newton-Euler equations [14]

$$M_i \frac{d\mathbf{V}_i}{dt} = \mathbf{F}_i, \tag{3}$$

$$\mathbf{I}_i \frac{d\mathbf{\Omega}_i}{dt} + \mathbf{\Omega}_i \times \mathbf{I}_i \mathbf{\Omega}_i = \mathbf{L}_i. \tag{4}$$

In these equations, $\mathbf{I}_i$ is the inertia tensor, M_i is the mass, and $\mathbf{F}_i$ and $\mathbf{L}_i$ are the external forces and torques acting on the particle i. The external force $\mathbf{F}_i$ acting on a solid particle contains forces due to gravity and due to contact between other solid particles and the PD container. Traditionally, the DEM approach was conceptualized for simple spherical particles [15]. Since the solid particles used in this work have complicated geometry, as seen in Figure 1, the traditional approach should be extended to accommodate contacts between arbitrary shapes. There are different approaches to compute the forces $\mathbf{F}_i$ and torques $\mathbf{L}_i$ for complicated shapes. One approach, as suggested in [16], is to represent a rigid particle of arbitrary shape by a set of spherical particles whose relative positions remain unchanged. In a more sophisticated approach, the particles of arbitrary shapes can be represented using triangular meshes and the contact forces could be computed proportional to the overlap volume between two such meshes. Moreover, by using fast collision detection algorithms such as the Bounding Volume Hierarchy approach [17], the simulation time can be reduced drastically. In this work, this sort of an approach is used to model contacts between non-convex shapes, which is readily available in the particle simulation software package Pasimodo [18].

3.3 SPH-DEM Coupling

In this paper, these hydraulic forces, which are exchanged between SPH and DEM particles, are described using an approach as in [7]. In this approach a set of virtual SPH particles are placed uniformly around the boundary of the DEM particle. These virtual SPH particles are basically meant to mimic the interface atoms between SPH and DEM particle in a macroscopic scale. This approach has been applied to fluid-structure interaction problems recently in [19, 20, 21]. Moreover, this approach was also used in the partially liquid-filled PD context involving spherical shaped solids in [4].

For time integration the explicit second-order Leapfrog scheme with time step control is used for all the simulations. Moreover, all the simulations are set up and performed using the particle simulation software package Pasimodo [18], which has been developed at the ITM for over a decade.

4 MODEL VALIDATION

In this section the coupled SPH-DEM model is validated against experimental data, which is generated using the ring-down experimental setup introduced in Section 2. The vertical leaf spring, which is used in the experiments, is modelled as a simple single degree of freedom spring-mass-damper system with the system parameters as identified in [4].

All the experiments and simulations presented in this section are conducted for an acrylic PD container of length $L = 100$ mm and inner diameter of 44 mm. In both cases, the PD container is loaded with 60 tetrapod shaped particles and 30 ml of distilled water. For the experiments each tetrapod particle is manufactured using a 3D printer, as seen in Figure 1. Moreover, each tetrapod has a bounding box dimension of d =8 mm and a density of $\rho_\mathrm{p} = 1200$ kgm^{-3}. On the simulation side the same geometry STL file, which was given as input to the 3D printer, is loaded in Pasimodo to represent the non-convex shape during all the simulations. The most relevant model parameters identified are listed in Table 1.

Table 1: Relevant parameters for the simulations

parameter	value
no. of solid particles n_p	60
solid density ρ_p (kgm^{-3})	1200
liquid density ρ_liq (kgm^{-3})	1000
liquid viscosity ν (Pa.s)	8.9×10^{-4}
CFL number	0.7
SPH smoothing length h (m)	7.5×10^{-4}

In Figure 2 (left), the velocity of the partially liquid-filled PD with tetrapod shapes, measured during experiments and predicted by coupled SPH-DEM simulation is compared. Figure 3 visualizes the motion of the damper contents as predicted by coupled SPH-DEM simulations. In order to better understand the effect of solid particles, the velocity damper filled purely with a liquid measured during experiments is also plotted in Figure 2 (left). Macroscopically seen, there is a good agreement between simulations and experiments, showing that coupled SPH-DEM simulations can adequately model the dynamics involved in a partially liquid-filled particle damper. It can be clearly seen, that the velocity decay is faster for the case with both liquid and solid filling, than for the purely liquid filled case. There are two possible reasons for this. First, the solid particles due to the hydraulic forces applied by the liquid, remain agile even under lower vibration amplitude, thereby leading to more effective collisions and in turn more energy dissipation. Secondly, the liquid is squeezed between two approaching solid particles leading to shearing of liquid layers. This ultimately results in more energy dissipation. In this case, the non-convex tetrapod particles behave effectively as obstacles to waves created by liquid motion. So in essence, the energy dissipation in case of a liquid-filled PD is due to the combined effect of increased solid particle agility and the sloshing motion of the liquid.

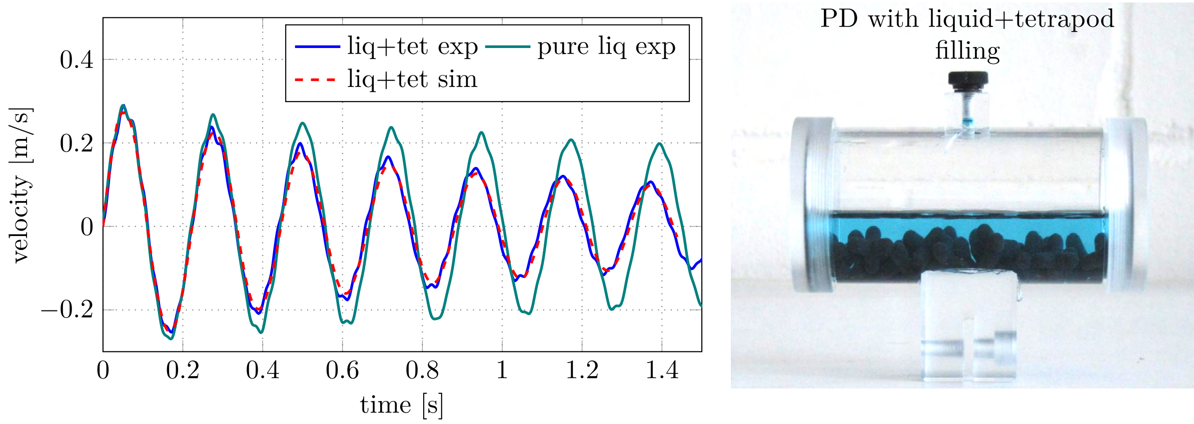

Figure 2: (left) The velocity of the damper container is compared for all the damper configurations. The red dashed line represents the container velocity predicted by coupled SPH-DEM simulations. The simulation and experiment are in good agreement. (right) The PD with liquid and tetrapod filling used in the experiments.

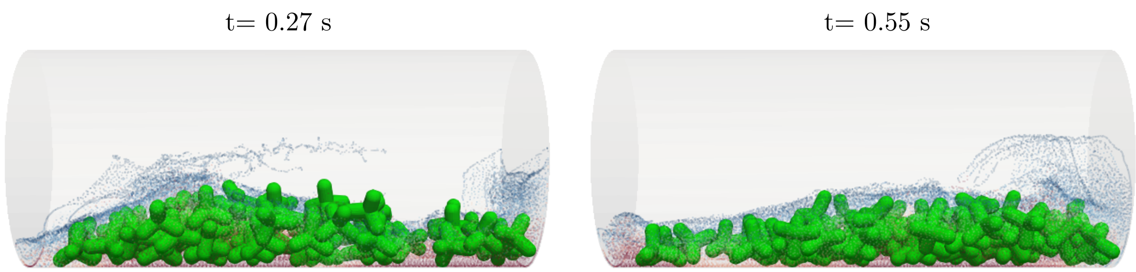

Figure 3: The motion of the damper contents, predicted by coupled SPH-DEM simulation, is visualized at two different time instances. The waves created by liquid motion are broken by the presence of agile solid particles. The fluid is visualized as colored balls, where the color gradient visualizes pressure from low (red) to high (blue).

5 INFLUENCE OF SOLID-LIQUID FILL RATIO

In the previous section it was seen that a combination of complex shaped solids and a liquid can substantially increase the dissipation performance. This newly gained insight rises a new question regarding the dynamics involved in partially liquid-filled PDs. What should the solid-liquid fill ratio be in order to maximize the dissipation rate? In order to gain further insights regarding this question a numerical investigation is performed.

In this numerical study the number of tetrapod solids are varied in three stages (0, 40, 60 solids) while the amount of liquid is kept at a constant 30 ml. By this way, the solid-liquid ratio is implicitly varied. For this study, the density of each solid tetrapod particle is chosen to be 7850 kgm^{-3}. While setting up the simulations, compensation masses were added to the system mass so that all the configurations have the same static mass. All the other parameters are carried over from Section 4 including the initial deflection of the spring which is 10 mm.

In Figure 4 (left) the simulated velocity decay for different solid-liquid fill ratios is compared and the corresponding average logarithmic decay rate is visualized in Figure 4 (right). It can be seen, that the decay rate for a damper filled purely with a liquid is lower than the PD with both solids and liquid. Moreover, increasing the number of solids particles seem to substantially increase the decay rate. This effect can be better understood using Figure 5 where the motion of the PD contents is visualized as predicted by coupled SPH-DEM simulations. Increasing the number of solid particles in the presence of a liquid effectively increases the number of solid particle collisions. Additionally, the liquid flow is observed to be more fierce with increase in the number of solid particles, leading to even more kinetic energy dissipation. With this investigation it can be said, that coupled SPH-DEM simulations can indeed be utilized to reliably predict complex dynamical effects present in partially liquid-filled PDs.

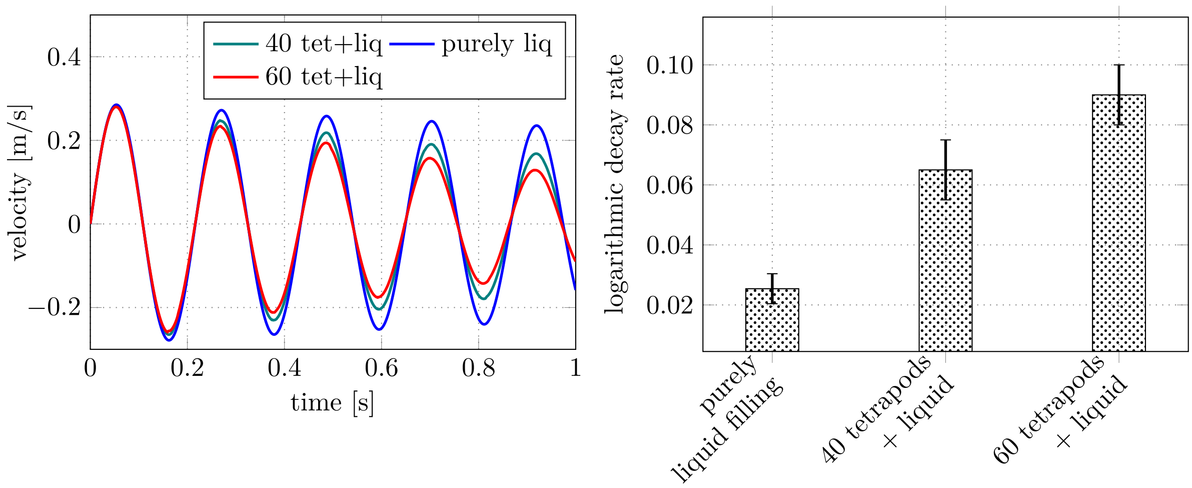

Figure 4: (left) The velocity of the damper container for various solid-liquid fill ratios is compared. (right) The average logarithmic decay rate, computed at the end of every cycle, is visualized with respect to different solid-liquid fill ratios.

6 CONCLUSIONS

In this work, it is shown that coupled SPH-DEM simulations can adequately predict the effect of complex particle shapes in enhancing dissipation performance of partially liquid-filled particle dampers. The tetrapod shape, inspired from coastal engineering, is the chosen particle shape for this investigation. In order to gain deeper insight into the various dissipation mechanisms and to increase confidence in the numerical models, experiments were performed. The experimental test bench is identical to the one used in [4] except that the solid particles were manufactured using a Stereolithography (SLA) 3D printer and have a different particle shape. A good agreement between experiments and simulations is observed on a macroscopic level. Both in simulations and experiments the partially liquid-filled PDs with non-convex particle shapes has superior damping performance than a purely liquid filled damper. The reasoning for this effect is twofold. Firstly,

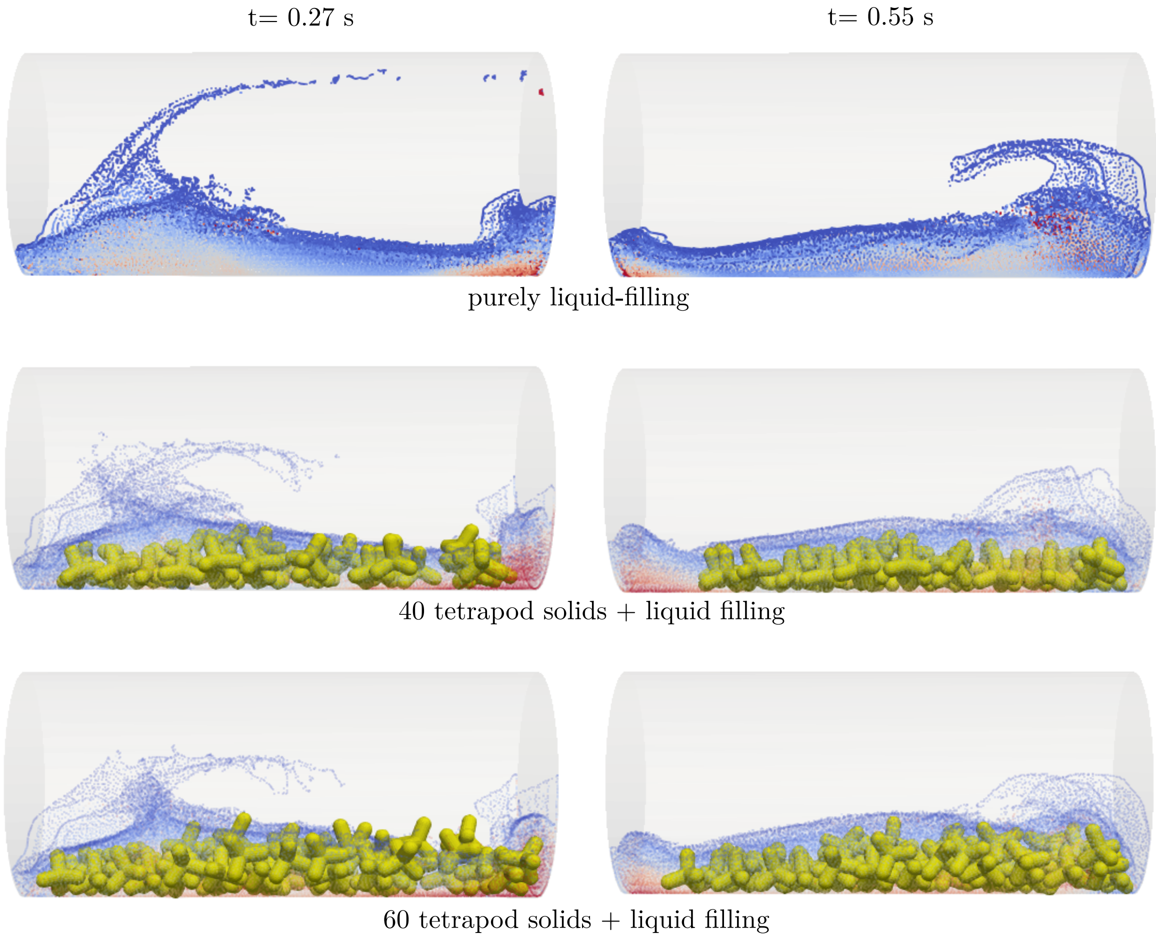

Figure 5: The motion of damper contents visualized for (top row) purely liquid filled damper, (middle row) 40 tetrapod solids + liquid and (bottom row) 60 tetrapod solids + liquid, at two different time instances. In all cases, the fluid is visualized as colored balls, where the color gradient visualizes pressure from low (red) to high (blue).

due to the presence of a liquid the complex shaped solid particles remain agile even under low vibration amplitude, leading to more effective collisions and in turn higher energy dissipation. Secondly, the liquid sloshing in the presence of complex shaped particles leads to more shearing between liquid layers causing more energy dissipation. In order to test these insights, a numerical study to understand the effect of fluid-solid fill ratio was set up. In this study, the solid-liquid fill ratio was varied by keeping the amount of liquid constant and varying the number of solid tetrapod particles. Adding more solids particles seemed to increase the dissipation rate. Since the solid particles carry more momentum than a liquid, the collisions between adjacent solids is much more effective leading to higher kinetic energy dissipation.

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