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Friction controls even submerged granular flows†

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We investigate the coupling between interstitial medium and granular particles by studying the hopper flow of dry and submerged system experimentally and numerically. In accordance with earlier studies, we find, that the dry hopper empties at a constant rate. However, in the submerged system we observe the surging of the flow rate. We model both systems using the discrete element method, which we couple with computational fluid dynamics in the case of a submerged hopper. We are able to match the simulations and the experiments with good accuracy. To do that, we fit the particle-particle contact friction for each system separately, finding that submerging the hopper changes the particle-particle contact friction from \( \mu_{\text{vacuum}} = 0.15 \) to \( \mu_{\text{sub}} = 0.13 \), while all the other simulation parameters remain the same. Furthermore, our experiments find a particle size dependence to the flow rate. We rationalize this finding based on arguments on the terminal velocity and drag: As is well known, larger particles are less prone to be influenced by the interstitial fluid.

1 Introduction

Understanding the coupling between solid particles and liquid is a challenging task due the complexity of grain-grain and grain-liquid interactions1,2. Even in vacuum the assemblies of granular particles exhibit highly complex dynamics. Depending on the loading and density, it can appear in gaseous, fluid-like or solid-like phases3. Related to this, the rheological characteristics of granular matter falls into the category of yield stress fluids4,5. However, their behavior is even more complex, as many of them show discontinuous shear thickening at intermediate shear6. Such an effect is attributed to the interparticle friction and/or the interlocking of the grains, depending on their shape7–9.

The 3D hopper flow, shown in Fig. 1, is a well studied model case of grain flow10–12, partly due to the fact that the geometry is simple allowing for easy implementation for the experimentalists, but also due to its importance in practical applications, from simple silos in farms to complex pharmaceutical factories. Even in a hopper flow, all three granular phases exist: the gas phase outside the hopper, the solid phase near the hopper boundaries, and the yielded (fluid) phase directly above the orifice enabling the flow.

Numerous studies have shown that in a dry hopper, the outflow of the granular particles follows the Beverloo equation13–15, which states that the grain outward flux remains constant in time.
until the hopper empties. The Beverloo equation for a dry case
\[ W_{dry} = C \rho \sqrt{g} (D - k d)^{5/2} \]  
(1)
describes the mass flow rate as a function of the density \( \rho \), gravity \( g \) as well as particle \( d \) and orifice \( D \) diameters. The term \( D - k d \) illustrates the empty annulus where the particles partially reduce the size of the orifice through constant \( k \). The exponent 5/2 can be derived through the so called free fall theorem that essentially says that the flow rate is proportional to the particle velocity as if it would freely fall from granular bulk forming a hemisphere above the orifice.\(^{16-18} \) The geometry then dictates the exponent 5/2. The Beverloo equation has the drawback that it only considers the dimensions of the grains and the orifice but not the properties of the interstitial medium, such as viscosity or drag.

Some studies have considered the role of air as an interstitial medium\(^ {19} \). There are simulations and experiments that show non-trivial flow patterns of air due to particle motion, showing oscillations non-trivial flow patterns of air due to particle motion, showing medium properties of the interstitial medium, such as viscosity or drag. These effects are in this case minor, since the drag caused by air is rather modest.

When the grains are embedded in a liquid, whose viscosity is orders of magnitude larger compared to that of air, the effect of interstitial medium is expectedly more pronounced.\(^ {23} \) Recently, the Beverloo equation was adapted and simplified to include the interstitial liquid\(^ {11} \)
\[ W_{go} = C \rho v_I d^2 (D/d - k)^2. \]  
(2)
Here the acceleration due to gravity in fixed distance is replaced by terminal velocity \( v_I \) of a single particle in a liquid. Here, we mark the flow rate \( W \) with a subindex \( go \) to emphasize that this is the reference flow rate for infinitely high packings with passive fluid flow at the steady state.\(^ {23} \) The empirical fit parameters are \( C = 0.4 \) and \( k = 2.4^{11,23} \). In addition, as opposed to a Newtonian fluid running out of a bucket, where the flow rate decreases as the fluid runs out, in the submerged granular system the flow rate of grains is observed to increase in time, i.e. surges.\(^ {11} \) In this submerged granular flow, the complexity of the problem rises from the fluid-particle interactions. As in the dry hopper scenario, the driving force of the system is the particle flow created by gravity. However, here the motion of the particles additionally creates fluid flow that disturbs the particle trajectories. This feedback loop between fluid and particles presumably increases the driving pressure of grains as they run out. A simple analytical model taking this into account is already shown in Reference.\(^ {23} \)

The article is organized as follows: It starts by introducing the reader to our Methods, giving the details of both the experiments and the simulations. Then in the section Results we describe the main findings, showing that the features observed in experiments are captured by the simulations. Once the validity of the simulation is confirmed, the values of grain-grain friction is varied in the simulations. The article finishes with Conclusions, where we discuss the results, and give the readers a short overlook to future research.

2 Methods
Here, we study both the dry and submerged granular hopper flows. In the simulations, we assume that we can model the dry case without the interstitial fluid (no CFD), since air viscosity and density are negligible. In contrast, the submerged granular flow comprises two distinct phases (granular particles and liquid) that interact by various forces and have to be modeled concurrently. The approach adopted here is to model the liquid phase on a continuum level and the granular phase as discrete particles. Specifically, the fluid phase is modeled by the Computational Fluid Dynamics (CFD) method,\(^ {24} \) which utilizes the Finite Volume Method (FVM) for discretizing the Navier-Stokes in the problem domain. The Discrete Element Method (DEM)\(^ {25} \) is applied for the granular (particle) phase and each particle trajectory is integrated individually based on the interaction forces.

In the CFD framework, the modified Navier-Stokes equations (NSEs)\(^ {26} \), physically implying the conservation of mass and momentum, are discretized and solved to yield the relevant quantities, such as the local fluid velocity and pressure fields. For an incompressible fluid, these read\(^ {1} \)
\[ \frac{\partial \varepsilon_f}{\partial t} + \nabla \cdot (\varepsilon_f \mathbf{u}) = 0, \]  
\[ \rho_f \varepsilon_f \left[ \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{u}) \right] = \nabla \cdot \mathbf{t} - ng_i + \rho_f \varepsilon_f \mathbf{g}, \]  
(3)
where \( \varepsilon_f \) is the fluid volume fraction, \( \mathbf{u} \) is the fluid velocity, \( \rho_f \) is the fluid density, \( \mathbf{t} \) is the Cauchy stress tensor and \( \mathbf{g} \) is the gravity term. Additionally, these modified NSEs include the particle-fluid interaction term \( (n \mathbf{E}) \), that contains the sum of the appropriate interaction forces over a number of particle \( n \), such as the (Di Feline) drag force\(^ {27} \), buoyancy, pressure gradient forces and the imposed shear stress\(^ {2} \). This term is also present in the DEM scheme, where it is included in the Newton’s 2nd law which is formulated and solved for each particle. More specifically, the equations of motion in DEM are\(^ {1} \)
\[ m_i \frac{\partial \mathbf{v}}{\partial t} = f_i + \sum_{j=1}^{n_i} (f_{r,ij} + f_{t,ij}) + m_i \mathbf{g} \]  
\[ I_i \frac{\partial \omega_i}{\partial t} = \sum_{j=1}^{n_i} (M_{r,ij} + M_{t,ij}), \]  
(4)
where \( m_i \) is the mass of particle \( i \), \( \mathbf{v} \) is the velocity of the said particle, \( f_{r,ij} \) and \( f_{t,ij} \) describe the elastic deformation and viscous energy dissipation of the particle while in contact with particle \( j \). Further, \( I_i \) is the moment of inertia of the particle while \( M_{r,ij} \) and \( M_{t,ij} \) describe the torque generated by tangential forces in a collision and rolling friction, respectively. Here, we have set the rolling friction to zero.

The presented coupling scheme has the inherent advantage of providing an accurate description of both the fluid and the particle phase at a reasonable computational expense\(^ {2} \). Furthermore, the CFD-DEM coupling is realized in a readily implemented software called CFDEM project which combines the OpenFOAM CFD-library with a DEM solver (LIGGGHTS\(^ {29} \)), providing the user ex-
tensive control over the simulation particulars and more importantly, the NSEs and fluid-particle interaction models. The implementation also grants efficient CPU parallel execution via the Message Passing Interface (MPI).

The material parameters used in the numerical method are obtained, where possible, from the experiments or utilizing textbook values. In the experiments, there are three types of grains, while in the simulations only the largest one is used. The grains are technical quality soda lime silica glass beads with \( d = 0.2 \pm 0.01 \text{ cm (A-205)}, \) \( d = 0.1 \pm 0.01 \text{ (A-100)}, \) and \( d = 0.05 \pm 0.005 \text{ (P-230)} \) in diameter from Potters Industries. Their density is \( \rho = 2.54 \pm 0.01 \text{ g/cm}^3 \) measured using the Archimedes method by sinking the beads in liquid and measuring the weight of the grains and fluid volume displacement. These values of the grain properties were set in the simulations to match the experimental values. The simulations additionally require knowledge of the elastic (Young’s and shear) moduli, and the friction and restitution coefficients. The typical values for Young’s and shear moduli of glass beads tabulated in textbooks are \( E = 72 \text{ GPa} \) and \( G = 30 \text{ GPa}, \) respectively. These give the Poisson’s ratio of \( \nu = E/(2G) - 1 = 0.2. \) The parameters used in the simulations are summarized in Tab. 1. It has been shown that a lower value of Young’s modulus can be used without affecting the results and this is also what we have observed while benchmarking our algorithm.

The friction and restitution coefficients, describing the dissipation of the grain-grain contacts and collisions, are the remaining parameters required to perform DEM simulations. Measurement of either of these for glass beads is impractical as it requires to estimate the dissipated energy in a dense granular flow. A textbook value for sliding of wet glass surfaces is around \( \mu = 0.1, \) which can be taken as a starting point for the simulations. A sensible value for the restitution coefficient of hard-sphere-like glass beads is \( \alpha = 0.9. \) For instance, in similar dry simulations involving softer grains, the restitution coefficient of \( \alpha = 0.8 \) has been used.

In the experimental setup, the liquid phase consists of filtered tap water at \( T = 22^\circ \text{C} \) temperature with the well known textbook values for viscosity \( \eta = 1.0 \text{ mPa·s} \) and density \( \rho_f = 1.00 \text{ g/cm}^3. \) Accordingly, these values were used in the simulations, with the further assumption of laminar flow conditions. Laminar flow can be safely assumed owing to the fact that the flow rates remain rather modest being purely driven by the release of the grains’ potential energy. In practice the hopper is submerged in a large fish tank. There are no water – air interfaces. The experiment is totally under water. The scale is above the water level, measuring the weight of the remaining beads in the hopper. The hopper is a flat bottomed cylindrical tube made of transparent polycarbonate with \( D_h = 5.0 \text{ cm} \) diameter. The orifice is a circular hole \( (D = 1.0 \text{ cm}) \) with 1 mm vertical walls that expand in 45-degree bevel cut at the center of the aluminum bottom. The experimental setup is described in detail in Refs. \(^{23,31} \) and their supplemental material.

Fig. 2 displays both the experimental 3D hopper (a) as well as its simulation counterpart (b). The initial state of the experimen-

| Table 1 | The values for the particle and fluid properties applied in the simulations and experiments. The more detailed technical information on the simulations is provided as Supplementary Data 1. The values marked with star are textbook values. |
|----------|--------------------------|--------------------------|
| **Granular particles** | simulation | experiment |
| Density of glass | \( \rho \) [g/cm\(^3\)] | 2.5 | 2.54 |
| Young’s Modulus | \( E \) [GPa] | 0.025 | 72* |
| Shear Modulus | \( G \) [GPa] | – | 30* |
| Poisson’s ratio | \( \nu \) | 0.2 | 0.2* |
| Restitution coefficient | \( \alpha \) | 0.9 | – |
| Timestep (DEM) | \( dt \) [\( \mu \text{s} \)] | 5.0 | – |
| **Fluid** | | | |
| Density of water | \( \rho_f \) [g/cm\(^3\)] | 1.0 | 1.0* |
| Viscosity | \( \eta \) [mPa·s] | 1.0 | 1.0* |
| Timestep (CFD) | \( dt \) [\( \mu \text{s} \)] | 50.0 | – |
| Coupling interval | \( d\tau \) [\( \mu \text{s} \)] | 500.0 | – |
tal hopper contains 50 % more beads than shown in Fig. 2(a). The red dye at the top was injected on top of the granular pile before the experiment and it propagates through the hopper faster than the grains can exit the system. (See the supplementary videos 1 and 2 which illustrate this process.)

The geometry is the same in the simulations and experiments, with very few exceptions. The initial filling height is smaller in the simulations, the hopper walls possess no thickness and have the same friction coefficient as the grains. The CFD simulation domain is divided into 1.5 million cells. The grid size gradually decreases near the hopper boundaries to ensure the quality of the solution in those areas. The meshing is realized applying the snappyHexMesh tool embedded in the OpenFOAM software.

In the simulations, the hopper flow is generated by first filling the hopper with the granular medium by pouring randomly the particles above the hopper top while the orifice remains closed. Then, once a sufficient filling height h is obtained, the granular packing is allowed to relax without the fluid for 0.5 seconds. At this point, the selection between the vacuum and submerged cases is made. In the vacuum case the orifice is opened, and the simulation is continued. In the submerged case, the coupled CFD-DEM simulation is initiated and the orifice is opened.

3 Results

Motivated by the large computational cost of the prescribed numerical simulations, we revisit our earlier experimental findings with a new perspective. The goal is to find a good compromise between having a long enough experiment with good surge per noise ratio (improves by reducing the particle size) and the computational burden (decreases with increasing particle size). The total particle number that can be handled with reasonable computational cost can be reached using the average grain diameter of d = 0.2 cm. Our main concern is the impact of the particle size on the surge. Hence, we start by comparing the earlier studied systems having d = 0.05 cm and d = 0.1 cm to the new system with d = 0.2 cm. For this purpose, we observe the flow rate and compute selected dimensionless numbers characterizing the systems.

Fig. 3 shows the relative flow rate against time t − tc, where the tc is the time when the flow stops. The flow rate W is obtained by differentiating the mass time series of the scale by fitting a 2nd degree polynomial in a 2 second Gaussian window similarly to Ref. 23. As we are interested on the surge and dynamic effects we scale the data by the reference flow rate obtained from the modified Beverloo equation (2). This operation allows us to compare the surge between the systems having different particle sizes.

The surge, the increase of flow rate W with respect to the asymptotic value Wgo decreases with increasing particle size as highlighted by the black arrow in Fig. 3. Also, the lifetime of the surge decreases when particle size increases which makes the comparison to simulations easier for larger particles than the small ones. The largest increase Wsurge = max(W) − Wgo is with d = 0.05 cm particles and the smallest is with d = 0.2 cm particles. This agrees with earlier findings as the surge term containing the fluid-grain coupling has d dependence as Wsurge ∝ (D − kd)2 (after expanding α from the supplementary material in Ref. 23). The surge Wsurge thus decreases when approaching the clogging region from below by increasing the particle size d. There is no flow, nor surge above the clogging region. We conclude that the large particles in our case approach to a limit where the granular aspect of the system starts to dominate. The inertia of the grains is too high for the fluid that there would be a large surge.

Figure 4 points out, that the superficial fluid velocity is faster than the grain velocity23. The fluid is faster and the inertia of the particles decreases the flow rate while the viscous component increases the flow. This counterintuitive result is consistent with the earlier results23 and illustrated in supplementary video 1 with a layer of dye that propagates faster than the grains can exit. With small particles the fluid flow dominates the process and particles reflect to this. The large particles have more momenta and inertia. The fluid flow cannot affect the particle motion. Then, the granular characteristics of the large particles dominate.

To obtain a more rigorous treatment we calculate dimensionless numbers that describe the flow. Table 2 describes the dimensionless numbers of the system. The Reynolds number Re = ρvvi d / η describes the ratio of inertial forces respect to viscous forces. It increases dramatically as the particle diameter increases (Re ≈ d2) indicating the increase of granular behavior at the expense of fluid flow, provided the grain properties (grain-grain friction, and grain size distribution) remain the same. At the same time, the drag coefficient decreases33, again, indicating the diminishing effect of fluid. Note that here we discuss only the laminar flow case. Finally we calculate the inertial number that is the ratio of confining pressure and shear rate i = ηγ/P 34,35. The inertial number I can be approximated by defining the shear rate γ = vi/(D/2) as velocity difference at the orifice and an approxi-
The Fluid-is-Faster effect is illustrated by plotting the trajectories of tracer particles. The green symbols represent the height of the granular column where the tracer particle is the highest particle at the side of the hopper. The blue symbols depict the lower edge of the dye. In the simulations, the blue dashed curve represents the vertical position of a single point-like virtual fluid tracer obtained by post processing the continuum fluid field. The green curve is the vertical position of one of the simulated grains. The figure shows that the fluid has a greater superficial velocity in both cases. The experiment and simulation are not directly comparable as the experimental values are averages while the simulation values are point-like measurements.

Table 2 Dimensionless numbers characterizing the system are the Reynold’s number (Re) and the inertial number I.

<table>
<thead>
<tr>
<th>d [cm]</th>
<th>Re</th>
<th>C_d</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>37</td>
<td>1.76</td>
<td>34.0 × 10^{-4}</td>
</tr>
<tr>
<td>0.10</td>
<td>151</td>
<td>0.86</td>
<td>17.0 × 10^{-4}</td>
</tr>
<tr>
<td>0.20</td>
<td>530</td>
<td>0.56</td>
<td>9.8 × 10^{-4}</td>
</tr>
</tbody>
</table>

where the effective density $\rho_e$ is the buoyancy corrected density. The particle geometry at the orifice is illustrated in Fig. 5. For small particles the inertial number is large, at the region where the dynamic effects already play a role. For large particles the inertial number decreases and the dynamic friction coefficient saturates (close) to static value. This is seen as a lack of terminal surge as a constant dynamic friction coefficient $\mu_{\text{sub}}$ takes 500 grams of grains in the dry case, while in the submerged case it takes 90 seconds.

Additionally, there is an acceleration of the flow rate at the end of the simulation (Fig. 6 insets). This is seen as separation of datasets and a slight downwards tilt in the data for the larger friction coefficients. Again, following the dry case, the low friction cases behave like Newtonian fluids without the acceleration. The contact friction of bulk granular materials is typically above $\mu = 0.1$. For these values, we find a surge like feature in the submerged simulation, lacking from the dry case. As the only difference between the dry and submerged simulation is the inclusion of fluid, we conclude that the surge is due to the coupling between the liquid and grains. In Fig. 7, we plot the simulated flow rate $W$ with multiple values of the friction coefficient $\mu$, creating an empirical relation between the initial flow rate $W$ and the friction coefficient $\mu$. Based on this empirical relation we deduce the friction coefficient by matching the flow rates in the experiments at $m = 300 \ldots 400$ g. The red open circles correspond to the dry simulations and the filled blue squares to the submerged simulations. The friction coefficients that reproduce the experiment are almost equal as $\mu_{\text{dry}} = 0.15$ and $\mu_{\text{sub}} = 0.13$ in the dry and submerged cases, respectively. The similarity in dry and submerged
friction coefficient is also reported by Dijksman et al. with acrylic beads in a rheometer\textsuperscript{38}. Note that here we refer to grain-grain friction whereas Dijksman et al. refers to the minimum friction coefficient $\mu_0$ at the quasi-static limit when inertial effects vanish $I \rightarrow 0$. The relation $\mu_0(\mu)$ is a non-trivial monotonic function that (to our knowledge) is only explored numerically\textsuperscript{37,39,40}.

Fig. 8 displays the mass of grains remaining in the hopper from both the experiments and the simulations with the friction coefficient set to the obtained values of $\mu_{dry} = 0.15$ in the dry case and $\mu_{sub} = 0.13$ in the submerged case. The submerged experiment is depicted in blue and the dry case in red color. The datasets are the result of a single run. The simulated and experimental data are overlapping within the measurement accuracy. This lends credence to the computational approach applied in the work and specifically suggests that the coupled CFD-DEM model captures the quintessential features of the two-phase (submerged) hopper flow.

The nonlinear surge effect is highlighted in the insert with a blue area that is the difference between a linear fit and the experimental data before the flow rate slows down. The blue area indicates a surge, the difference between linear Beverloo behavior and measured data.

Fig. 9 displays the Gaussian weighted derivative over two sec-
Fig. 9 The derivative of hopper mass over time shows the surge in submerged case for both experiments (blue +) and simulations (solid curve). The surge is not seen in the dry experiments (red x) and simulations (solid red). However, the final moments of the dry experiment might contain a tiny surge that is too fast for the current experimental procedure and analysis.

ond time window of the data depicted in Fig. 8. In both dry cases, the experiment and the simulation, the hopper empties at a constant flow rate. At the end when the grains run out and the flow rate decreases without a terminal surge. In contrast, the presence of the interstitial fluid reduces the overall granular flow rate and imposes an acceleration towards the end. Recently, such terminal surge has been confirmed in the dry case for smaller particles in experiments and appears to be visible also in simulations.

Based on our theoretical discussion on the terminal velocity, and on the dependence of the surge on particle size, we propose that the 2 mm particles are too heavy to be affected by interstitial air. Therefore, the surge does not appear in the dry experiments resulting in good agreement to our vacuum simulations. Since the viscosity and density of water are several orders of magnitude larger, the submerged flow exhibits a surge. We conclude that the viscosity of the interstitial medium has to be large enough compared to the particle inertia for the surge to appear.

Flow sensitivity to friction coefficient gives the possibility to interpret the hopper flow in the context of non-linear effective rheology. Fig. 10 shows a schematic illustration of three systems with (discontinuous) shear thickening, a characteristic of frictional granular systems. For the same load, caused by the high particle column, the frictionless case, a Newtonian fluid, has the smallest slope and thus lowest effective viscosity. Friction increases the slope and introduces a sudden increase of viscosity, that can be many orders of magnitude. When the mass \( m(t) \) of the particle column decreases in time, the effective viscosity of the system decreases as well, causing an increase in the flow rate. This is seen as the terminal surge.

Fig. 10 A schematic illustration of three materials with discontinuous shear thickening. The increasing contact friction of the particles leads to decreasing flow rate. At continuum, this can be interpreted as increasing effective viscosity \( \eta \), that increases with particle friction for high shear stresses.

4 Conclusions

We performed experiments and simulations on dry and submerged hopper flows of granular particles of approximately millimeter radius using the combination of DEM and CFD. In the dry frictionless case, we confirm the previously known numerical result, that the flow rate of the dry granular particles decreases as a function of time. In addition, we find the same behavior also for the frictionless submerged system. This scenario could be understood in the context of a Newtonian fluid running out of a hopper.

For dry frictional particles we confirm that the flow rate remains constant until the height of the granular column is less than the width of the hopper. Thus, the grain-grain friction changes the scenario from a Newtonian behavior into a more complex one, readily described by the Beverloo equation.

In the submerged hopper case, the grain-grain friction causes the flow to accelerate through the whole hopper emptying process. Furthermore, right before the hopper runs out of grains there is a clear terminal surge in the flow rate. The accelerating flow can be understood via a simple scenario of a feedback loop mediated by the incompressible, viscous water: The grains exit the hopper as gravity pulls them. Outside the hopper, the grains replace water, which due to the incompressibility enters the hopper mainly through the open top where the flow resistance is the smallest. This creates a flow of water through the granular packing. It, in turn, due to the viscous drag, pulls more grains out from the hopper increasing the outflow of the grains. This granular pumping effect is described in and is captured by the simulation here.

As we observe, both the dry and submerged cases are sensitive to the grain-grain friction. This allows us to use the parameter to fit the simulated flow rates against the corresponding experi-
ments. Subsequently, we observe that the best fit friction parameter is almost the same in both the cases. This was a surprising result, since one would expect the grain-grain friction to be significantly lower between the grains. However, as we do not explicitly account for the grain-grain hydrodynamic interactions, we expect the friction coefficient to partly compensate for that.

In this paper we show that one can successfully capture both qualitatively and quantitatively this counter intuitive behavior arising in a submerged granular hopper flow using coupled discrete element model (DEM) for the particle dynamics and computational fluid dynamics (CFD) for the liquid. While the particle trajectories and interactions are computed explicitly in the DEM-implementation, the fluid flow is modeled on a continuum level by the CFD approach. This is fundamentally different from the inertial $\mu(I_\ell)$-model where the granular media and the interstitial fluid is treated as a single continuum.\[45\]

Here we have presented the first step to compare simulations and experiments of a submerged hopper flow with a good agreement. The one-to-one match with experiments and simulation is currently pushing the limits of both methods. Using smaller than $\Delta = 0.2$ cm particles increases the experimental accuracy via lowering the flow rate. However, using smaller particles in the simulations renders them impractical by making the problem too large for the present computational resources. Both of these problems, the experimental and numerical may be solvable in the near future by advanced computational methods such as coarse grainings of particles in the bulk\[46,47\] and experimental measurement techniques such as identifying and counting individual particles. Future studies could involve the effect of wall and bottom friction, dilation of grains at the orifice, clogging, self-generated pumping of fluid, terminal and exit velocities of particles, and the behavior of $W_{60}$ as a function of particle size. For $W_{60}$ there should be a transition from colloidal no-flow behavior to surging flow and back to no-flow at clogging, which unfortunately fell outside the scope of this paper.

5 Conflicts of interest

There are no conflicts to declare.

6 Acknowledgement

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