Chapter 6

Particle resuspension

6.1 Motivation

In previous chapters, the relative effective viscosity of a flow with particles denser than the interstitial liquid was discussed. Such results show that these flows exhibit a shear thickening behavior when the amount of particles loaded is less than 30% in volume, while for flows with particle loading higher than 30% the behavior exhibited was shear thinning. In this chapter, the results of the visualization of such flows are presented to understand the mechanism behind such behaviors and to further explore the resuspension of flows consisting of settling polystyrene particles.

6.2 Particle settling

The visualizations are made by using the visualization setup described in Chapter 2, where the test cylinder and top fixed guard are replaced by a transparent acrylic cylinder. As described in Chapter 2, the acrylic cylinder wall is roughened in the same manner as for the torque measurements, leaving only a portion of the wall smooth and which serves as a visualization window. A percentage of approximately 20% in volume of particles is painted on one face to make the visualization process easier. The interstitial liquid for all the cases describe in this chapter is water and the particles are all polystyrene; thus the density ratio between the particles and the liquid is $\rho_p/\rho = 1.05$. For each set of experiments, a known volume of particles is loaded into the annulus. The volume of the particles is obtained by carefully adding the particles to a known volume of water until they all sink, and then measuring the volume of water displaced. The loading volume fraction ($\bar{\phi}$) is the ratio between the volume of particles loaded and the total annulus volume. Each experiment is prepared by running the rheometer for 30 minutes at a shear rate of, $\dot{\gamma} = 50\ s^{-1}$, with the objective to remove air bubbles from the mixture and guarantee a homogeneous distribution of the particles. Once the mixture has been sheared for 30 minutes, the rheometer is brought to a complete stopped and the particles are allowed to come to rest in a loose, random orientation. Observations through the visualization window show that the particles settled and stop moving in less than a minute. However, pictures of the apparent settle column of particles taken several minutes later show that the minimum settling height of the column is not reached once the particles stop moving but some time after that. An image sequence of the particles settling is shown in Figure 6.1.

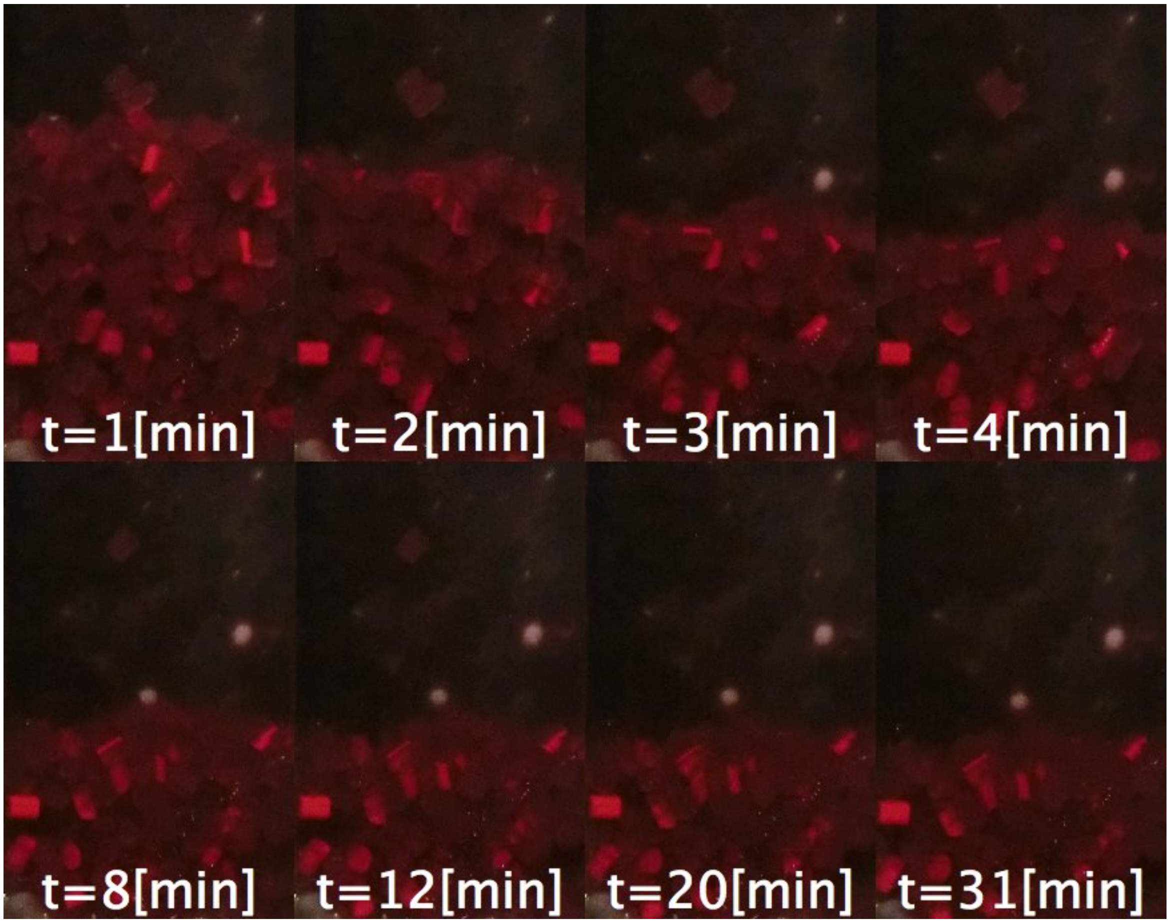

Figure 6.1: Settling process after the rheometer is brought to a complete stop for a loading volume fraction of 25%. Polystyrene particles, $\rho_p/\rho = 1.05$. Pictures taken from inside the inner cylinder. Each window has a width of approximately 3.8 (cm) and the bottom of each picture corresponds to the top of the lower fixed guard.

The height of the settled particles is measured by drawing a line that follows the top contour of the particles. The vertical coordinates along the contour are considered and averaged to obtain the particle's mean height. An example of the contour used to measure the settled particle's height is shown in Figure 6.2

The minimum loading volume fraction that could be studied is 20%. For lower loading volume fractions the particles are below the visualization window. In Figure 6.3 the ratio of the height of the settled particles (h_s) and the total annulus height (h_t) of the rheometer for a loading volume fraction of 25% is shown. The particle's packing decreases approximately 2.54 cm and reach a

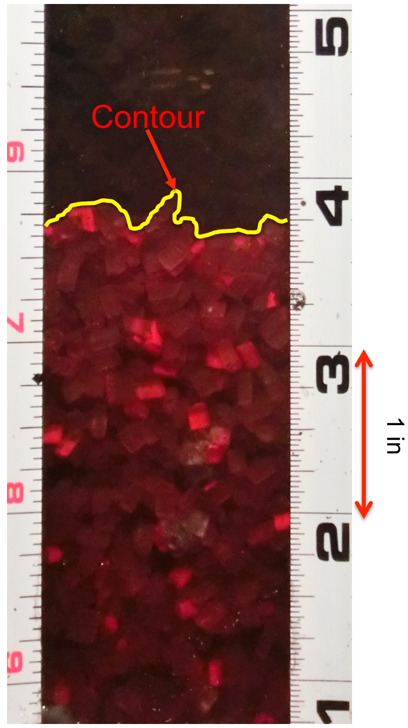

Figure 6.2: Settled particles and their contour marked by the yellow line. The case shown corresponds to a loading volume fraction of 30%. The ruler shown is in inches. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$.

minimum constant height in 20 minutes. The height of the settled particles decreases by a total of 10.6% of its initial length.

To compare the settling process between different loading volume fractions, the minimum height was subtracted from the measured heights for each loading volume fraction and normalized by the total annulus height. Figure 6.4 shows how much the settled particles compact with time. An average of 15 minutes is the time it takes for the particles to reach a minimum height. From Figure 6.4 it can be seen that the height difference $(h - h_{min})$ increases with the loading volume fraction; that is, the higher the amount of particles there is, the more the particles compact.

Figure 6.5 shows the height of the settled particles normalized with the annulus total height as a function of the loading volume fraction. The normalized height exhibits a linear relation with the loading volume fraction. The linear fit does not intercept the origin and therefore cannot be used to predict the height for lower loading volume fractions. For very low loading volume fractions the particle's height may show a different dependance with the loading volume fraction. This could be better seen by considering a very low loading volume fraction where the number of particles is not enough to completely cover the base of the annulus. For such a case the presence of a few extra particles strongly influences the measured height; meanwhile, for higher loading volume fractions the mean measured height is not be affected by the presence of a few extra particles. Note that

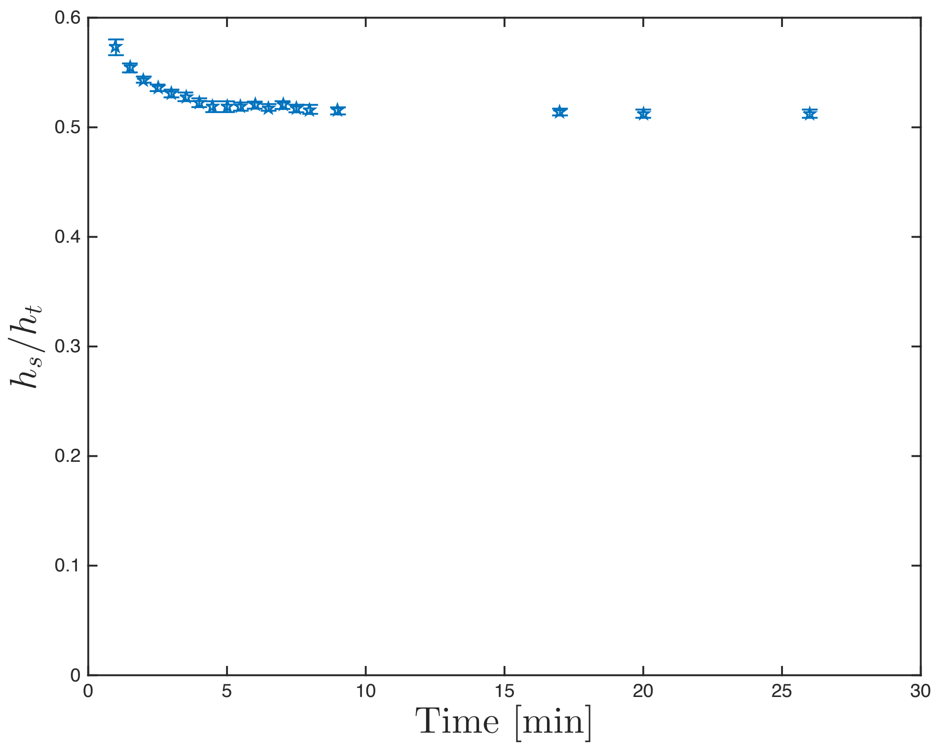

Figure 6.3: Settled particles height (h_s) normalized with the total annulus height (h_t) as a function of time for a loading fraction of 25%. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. The vertical error bars correspond to the standard deviation of the height measurements, while the horizontal error bars represent the uncertainty in the time at which the corresponding picture was taken.

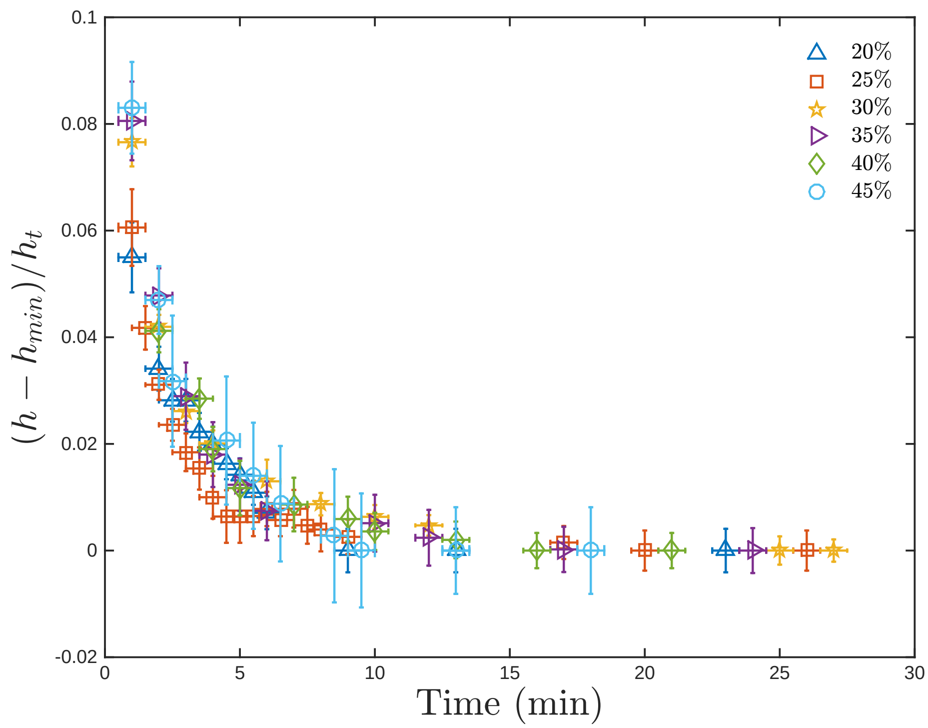

Figure 6.4: Difference of settled particles height and its minimum (h_{min}) normalized with total annulus height (h_t) as a function of time for different loading volume fractions for polystyrene particles. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. The vertical error bars correspond to the standard deviation of the height measurements, while the horizontal error bars represent the uncertainty in the time at which each picture was taken.

if the linear fit in Figure 6.5 is extrapolated to $h_s/h_t = 1$, the loading fraction is 55.8, which is approximately equal to the random loose packing measured by Koos (2009).

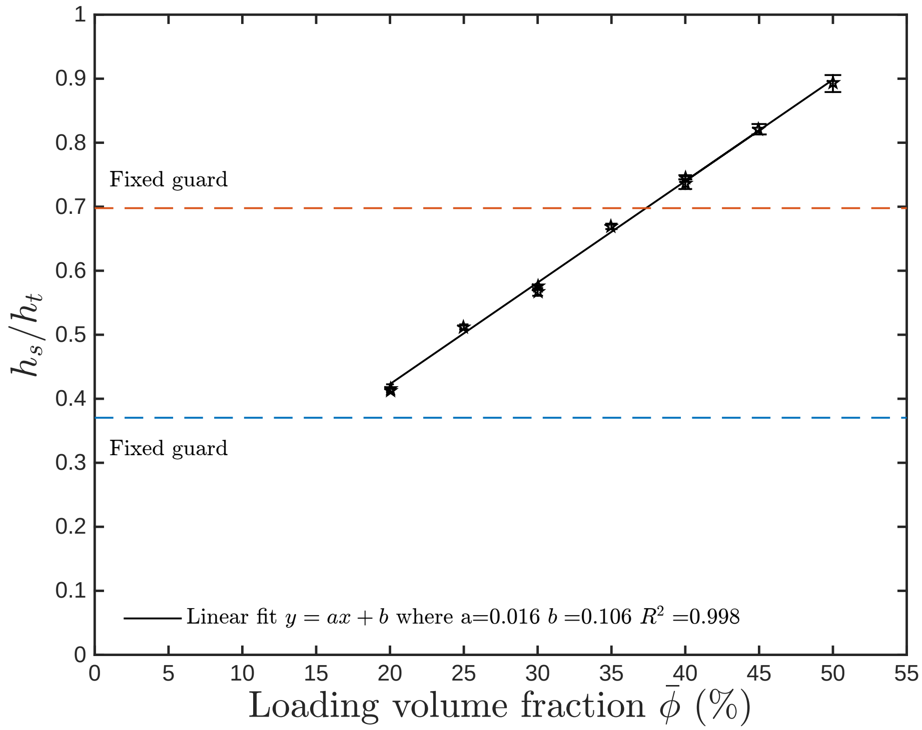

Figure 6.5: Settled particle's height (h_s) normalized with the total height of the rheometer annulus (h_t) as a function of the loading volume fraction. Dashed lines correspond to the relative position of the low and top fixed guards. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the height measurements standard deviation.

Particle settling over a porous medium

Visualizations are also made for the case of a flow over a porous medium where the rheometer is filled with spherical glass beads (diameter of 4 (mm) and density of 2520 (kg/m^3)) up to approximately 6/7 of the bottom fixed guard. Polystyrene particles are placed on top of this layer of glass beads, as described in Chapter 5. The density ratio between the polystyrene particles and the interstitial liquid (water) for the experiments described in this section is $\rho_p/\rho = 1.05$. The volume of the annulus considered for these experiments does not take into account the volume occupied by the glass beads. Therefore, the volume of polystyrene particles needed to obtain a loading volume fraction of 10% is less than for the case with no glass beads on the bottom (approximately 33% less in particles volume). To account for the volume occupied by the porous medium, measurements of its height are conducted, and from this the packing of the porous medium is calculated. As described in Chapter 2, the porous medium is prepared by first measuring the volume of the glass beads. This is done by pouring them into a known volume of water and measuring the volume of liquid displaced. Then, the known volume of glass beads is poured into the bottom part of the annulus and it is evenly distributed along the perimeter of the rheometer. Once the entire volume of glass beads is poured and evenly distributed, the porous medium is sheared to account for any change in packing due to shearing (to prevent excessive shearing on the porous medium, the walls of the bottom part of the rheometer are not roughened). The height between the top of the lower fixed guard and the porous medium is measured with the help of a vernier. These measurements are made dry and it is considered that the effect of water on the packing of glass beads is negligible due to the high density of the glass beads. A packing of 0.62 is found, which is what Koos (2009) measured for the random loose packing of spherical glass beads of 3 mm in diameter and with the same density.

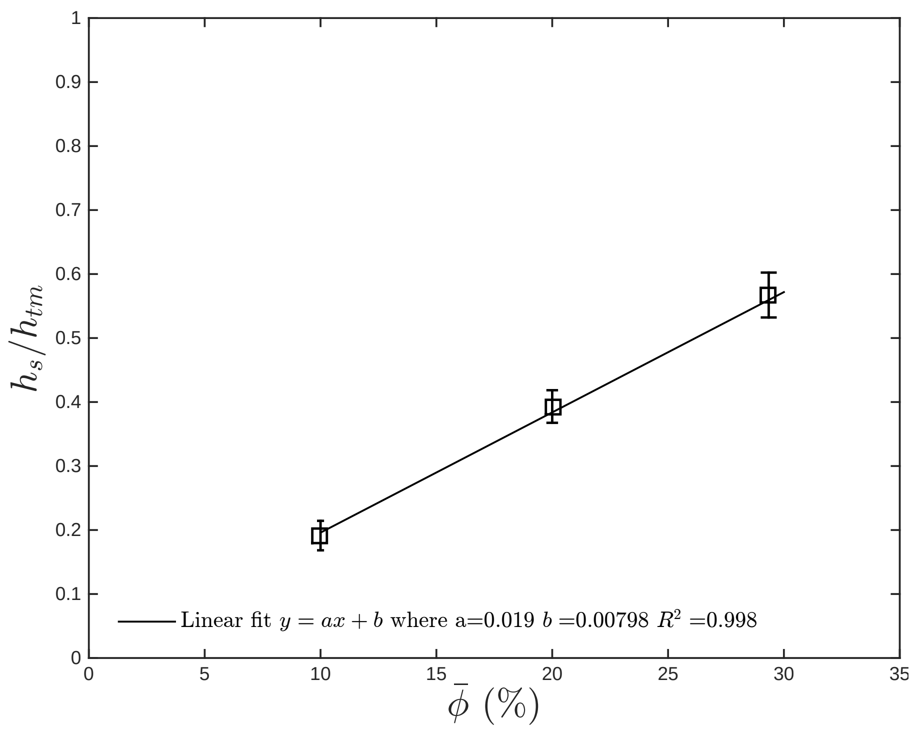

Figure 6.6: Settled particles height (h_s) normalized with the total height of the annulus modified for the presence of porous medium (h_{tm}). The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the height measurements standard deviation.

Figure 6.6 shows the settled particles height normalized by the height between the top of the glass beads' bottom layer and the top of the rheometer annulus (h_{tm}). As with the previous measurements for the height of settled particles, the relation between the loading volume fraction and h_s is linear and the fit does not intercept at the origin. Figure 6.7 shows the settling height normalized by the annulus total height (h_t) for the experiments with and without porous medium. The difference in normalized height for the same loading fraction between experiments is due to the presence of the porous medium. With a porous medium, even for a low loading fraction of 10%, the particles' height is always above the bottom fixed guard. Figure 6.8 shows the settling heights for the experiments with porous medium normalized by the modified annulus height (without considering the layer of glass beads) and the non-porous medium heights normalized by the total annulus height. For the experiments with porous medium, the particles height is slightly lower than for the case with no porous medium. The little difference between the normalized heights has a more pronounced effect when the random loose packing is measured, as discussed in the next section.

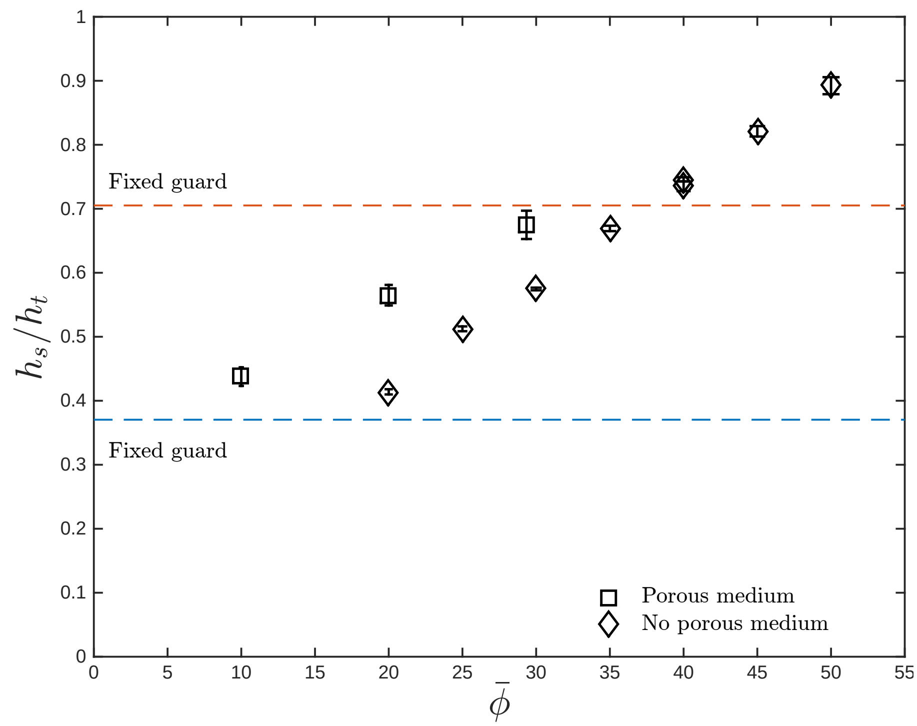

Figure 6.7: Settled particles height (h_s) normalized with the total height of the annulus (h_t) for experiments with and without porous medium. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the height measurements standard deviation.

6.3 Random loose packing

The random loose packing, ϕ_{RLP}, can be calculated from these height measurements by considering that the total volume occupied by the particles is equal to the measured settled height times the area of the base of the rheometer annulus. The height measured through the visualization window is considered to be the same along the perimeter and in the radial direction of the rheometer. The reduction in the annulus base area due to the rough surface is considered when calculating this area. The random loose packing is then be given by

$$\phi_{RLP} = \frac{\text{Volume of particles}}{\text{Volume occupied by particles}} = \frac{\text{Volume of particles}}{\text{Annulus base area} \times h_s}, \tag{6.1}$$

where h_s is the minimum settling height reached by the settled particles after 15 minutes or

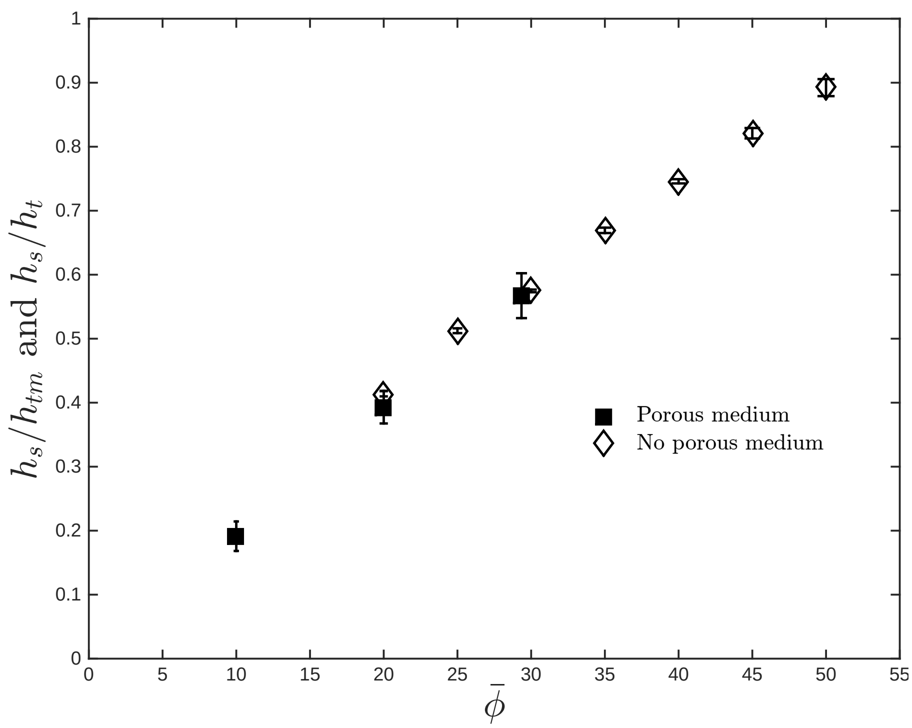

Figure 6.8: Settled particles height (h_s) normalized with the total height of the annulus (h_t). For the experiments with porous medium, the settling height is normalized by the modified total height annulus (h_{tm}). The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the height measurements standard deviation.

more have passed. Figure 6.9 shows the random loose packing as a function of the loading volume fraction. As seen in Figure 6.4, the higher the loading volume fraction, the more the particles are compacted, which leads to a higher random loose packing. One of the sources of uncertainty for the random loose packing calculation is the area considered for the annulus base. To verify that the annulus base area is constant along the vertical axis, measurements of the height of a known volume column of water are performed. These measurements show that the column water height increases linearly with the water volume. Hence, the annulus base area seems to be constant along the annulus height. The annulus base area can be measured from these measurements; however, the area occupied by the water is larger than the area that can be occupied by the particles, since the water can enter cavities in the rough surface that the particles can not. For this reason, the annulus base area is considered to be equal to $\pi \times ((r_o - d)^2 - (r_i + d)^2)$, where r_o and r_i are the outer and inner cylinder radius with smooth walls and d is the particle diameter.

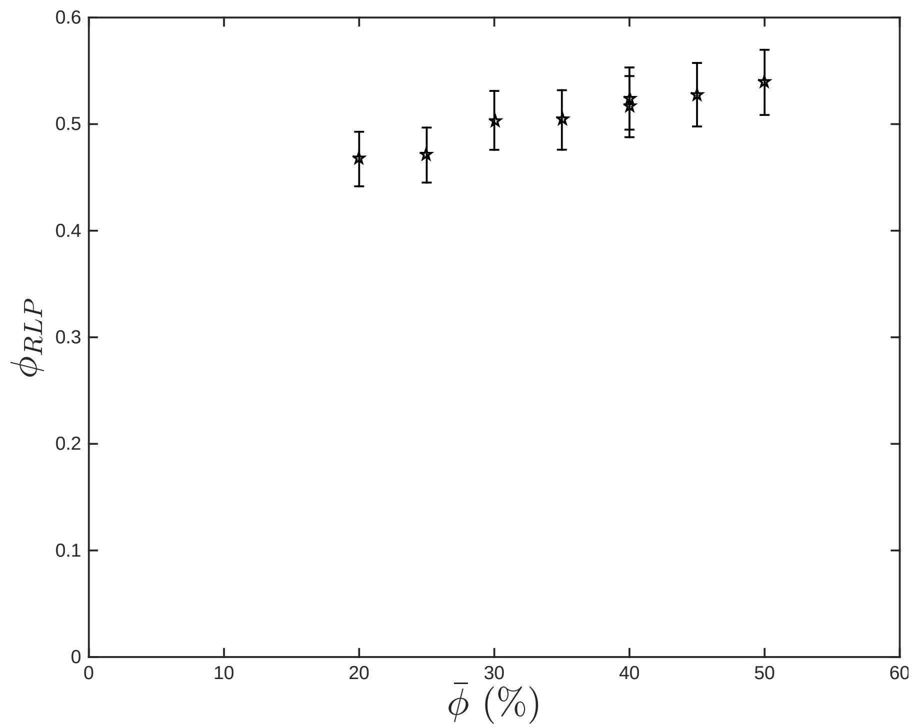

Figure 6.9: Measured random loose packing from the settling height measurements as a function of the loading volume fraction. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the uncertainty involved in these measurements.

The reason why the random loose packing is not constant is still not completely understood, but one explanation could be the effect that the extra weight due to the increase in particles has on further compacting the column of particles. Moreover, it is likely that some particles have a lighter density, leading to higher measurements of the particle column height and thus a decrease in the random loose packing calculated. The ratio between the random loose packing for the highest and lowest loading volume fraction is 1.16; thus the random loose packing varies up to 16% for different loading volume fractions.

Random loose packing of polystyrene particles over a porous medium

The random loose packing is calculated for the loading volume fractions of 10, 20 and 30 percent. Higher loading volume fractions are not measured because the view window only covered the height of the test cylinder, which is lower than the height of the particles. As mentioned before, the volume of the annulus considered when there is a porous medium on the bottom of the rheometer depends on the packing of such medium.

The polystyrene particles' column height is measured in the same way as for the previous cases, where the mixture is sheared for several minutes to ensure a homogeneous distribution of the particles and then brought to rest. Figure 6.10 shows the random loose packing calculated for the settled particles over a porous medium. As with the previous random loose packing measurements, the

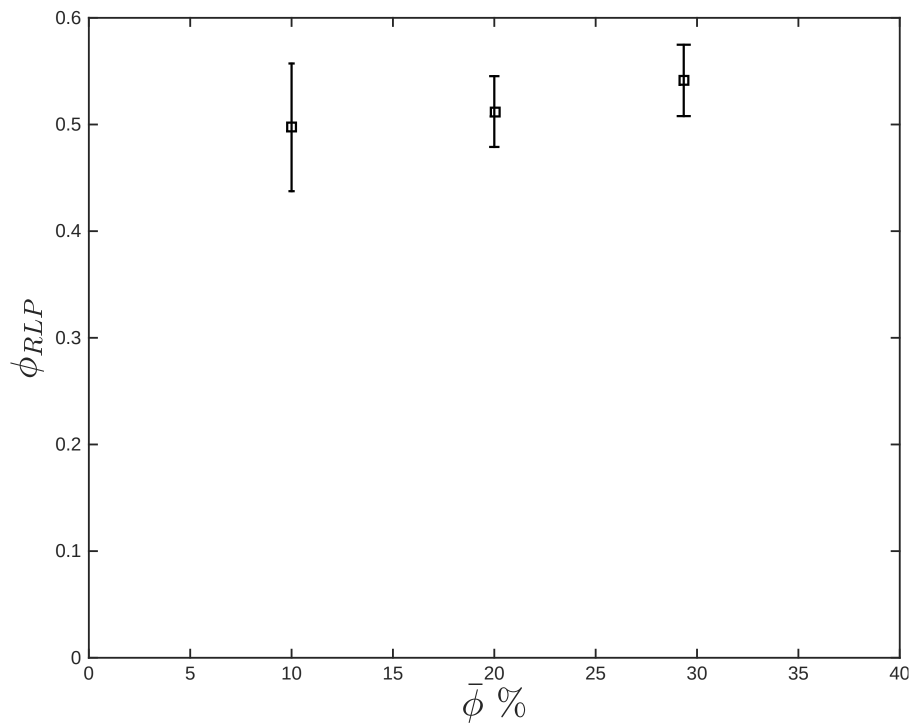

Figure 6.10: Measured random loose packing from the settling height measurements of polystyrene particles over a porous medium as a function of the loading volume fraction. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the uncertainty involved in these measurements.

ϕ_{RLP} increases with loading volume fraction. The random loose packing for polystyrene particles over a porous medium can be compared to the one measured without porous medium on the bottom. Figure 6.11 shows this comparison. For all the loading volume fractions, the random loose packing

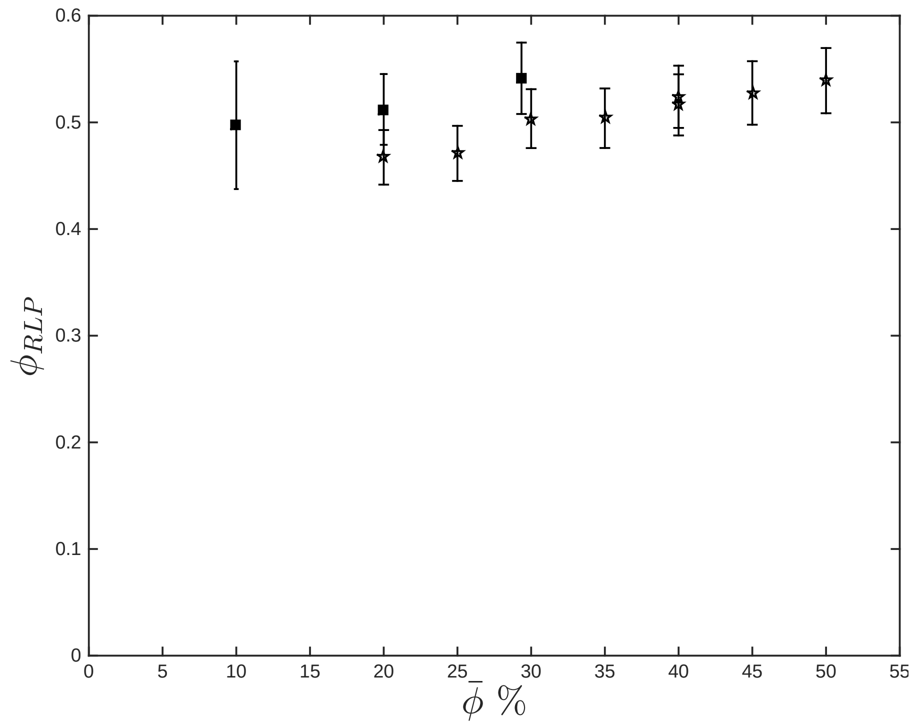

Figure 6.11: Comparison between measured random loose packing of polystyrene particles with and without a porous medium on the bottom as a function of the loading volume fraction. The ratio between particles and fluid density is $\rho_p/\rho = 1.05$. Error bars correspond to the uncertainty involved in these measurements.

for the cases with glass beads on the bottom is higher than for the case without glass beads. However, the random loose packing for the case without porous medium is within the lower error bar for the ϕ_{RLP} with a porous base. Besides the porous medium, these two cases differ in the amount of particles necessary to reach the same loading volume fraction. There are less particles for the case with porous medium, which makes the topology of the particles' top surface a source of greater uncertainty.

6.4 Particle resuspension for $\rho_p/\rho = 1.05$

The characteristics of settled polystyrene particles immersed in water are discussed in the previous section. For all the cases presented in the previous section the Stokes and Reynolds numbers were equal to zero. In this section, the resuspension of the particles due to an increase in the shear rate and consequently an increase on the Stokes and Reynolds numbers is studied. The case without porous medium on the bottom is analyzed first. For all the experiments studied in this section the interstitial liquid of the flow is water and the density ratio between the particles and the liquid is $\rho_p/\rho = 1.05$.

Figure 6.12 shows an image sequence of the resuspension for a loading volume fraction of 25 %. Each picture is taken after several minutes of shearing the liquid-solid mixture at the shear rate corresponding for each Stokes number. As Stokes number increases, the particles start fluidizing until they reach a steady state where the level reached by the particles remains constant with time. The level reached by the particles for each Stokes number is measured in the same way as the height of the column of settled particles (described in the previous section). A minimum of 9 pictures for each Stokes number is taken and used to measure the resuspension height. Figure 6.13 shows the resuspension height normalized by the total height of the rheometer annulus.

The change in height occurs abruptly as the Stokes number is increased from zero, as shown in Figure 6.12 and 6.13 . The height normalized by the annulus height, as shown in both figures, for $St = 0$ corresponds to the settled particles' height after the particles have been at rest for more than 15 minutes. The further packing of the particles while at rest described in Section 6.1 contributes for this sudden change in height. A similar profile is observed for different loading volume fractions, as shown in Figure 6.14.

The normalized resuspension heights increase with loading volume fraction but exhibit a similar dependance on Stokes number. This suggest that the data could be collapsed into one curve, and such a parameter can be the particles packing. For St=0, the random loose packing is measured and described in detail in Section 6.3. A volume fraction for non-zero Stokes numbers is given by:

$$\phi = \frac{\text{Volume of particles}}{h \times \text{Annulus base area}} = \phi_{RLP}\frac{h_s}{h}, \tag{6.2}$$

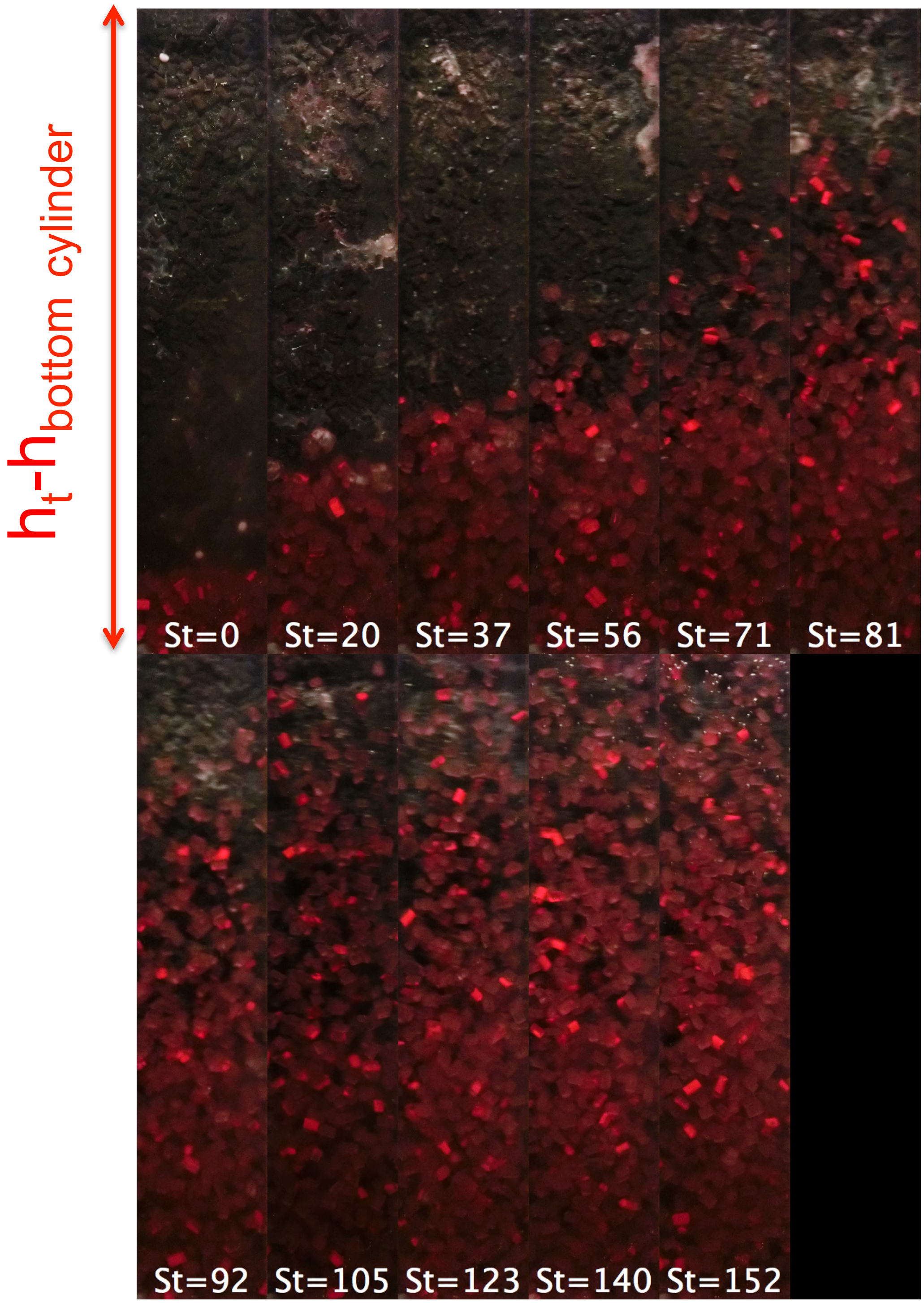

Figure 6.12: Particles resuspension for a loading volume fraction of 25% for different Stokes numbers. Pictures taken from inside the inner cylinder. Each window has a width of approximately 3.8 (cm) and a height equal to the total rheometer annulus height minus the lower fixed guard height. The bottom of each picture corresponds to the bottom of the test cylinder.

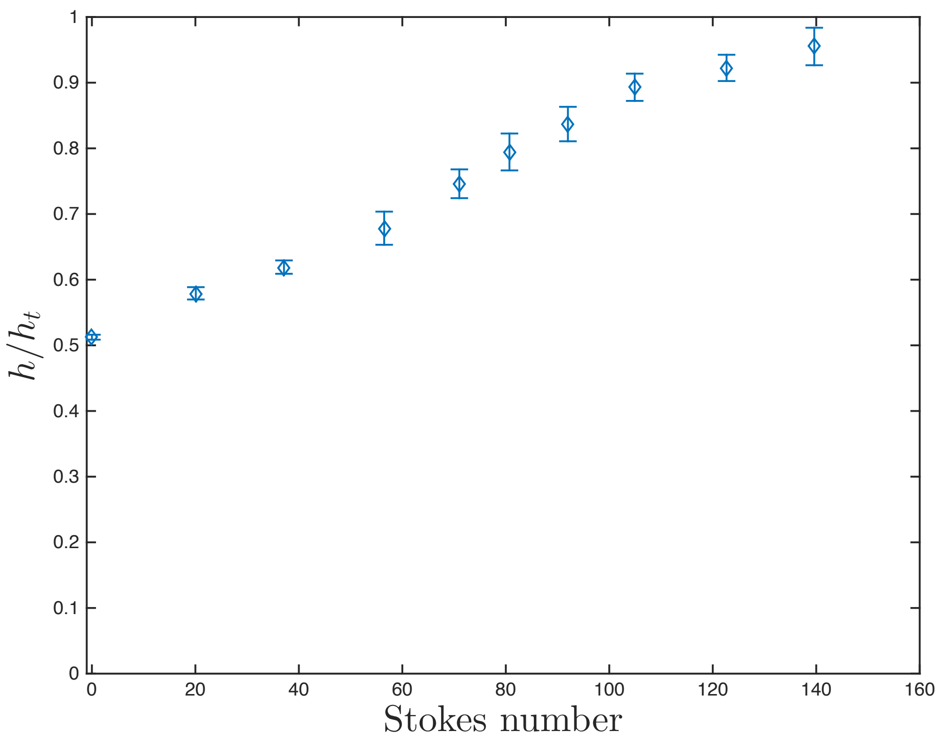

Figure 6.13: Resuspension height (h) normalized by the total rheometer annulus height (h_t) as a function of Stokes numbers for a loading volume fraction of 25%. Error bars correspond to the standard deviation in the resuspension height measurements.

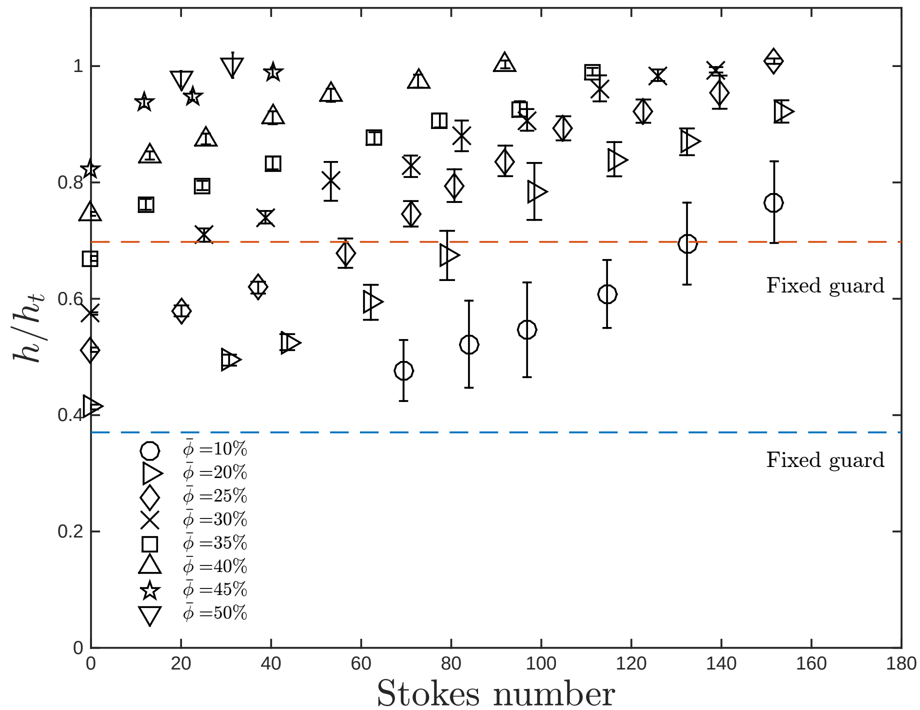

Figure 6.14: Resuspension height (h) normalized by the total rheometer annulus height (h_t) as a function of Stokes numbers. Error bars correspond to the standard deviation in the resuspension height measurements.

where h_s is the settled particles' height and h is the resuspension height. Figure 6.15 shows the particles packing's strong dependance on Stokes number. There is some dependance on the loading volume fraction but this can be further minimized if the particles packing is normalized by the measured random loose packing for each loading volume fraction as shown in Figure 6.16. Predictions of how much the particles would expand given a certain Stokes number can be done using this relation. Such predictions are used in the next chapter to predict the effective volume fraction of the torque measurements.

Particle resuspension over a porous medium ($\rho_p/\rho = 1.05$).

The analysis of the resuspension of settling particles over a layer of glass beads (porous medium) is done in a similar way as discussed in the previous section. Only the total rheometer annulus height is reduced to take into account the bottom layer of glass beads. The height for this type of experiments is measured from the top surface of the porous medium. Figure 6.17 shows the resuspension height normalized by the modified total annulus height (h_{tm}). As with the previous experiments, the normalized height increases with the Stokes number and with the loading volume fraction. To study the effect of the bottom glass beads layer on the resuspension, the heights are normalized by the modified total height and compared with the normalized measured heights for the

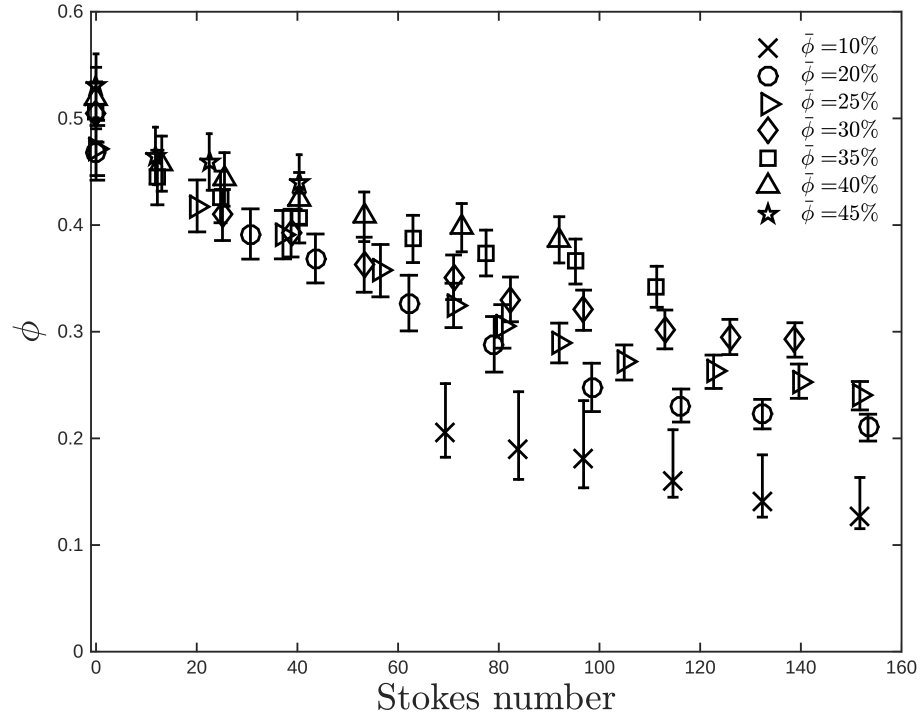

Figure 6.15: Particle packing for different loading volume fractions as a function of Stokes numbers. The uncertainties in measuring the particles packing are combined in root mean square sense and are represented by the error bars.

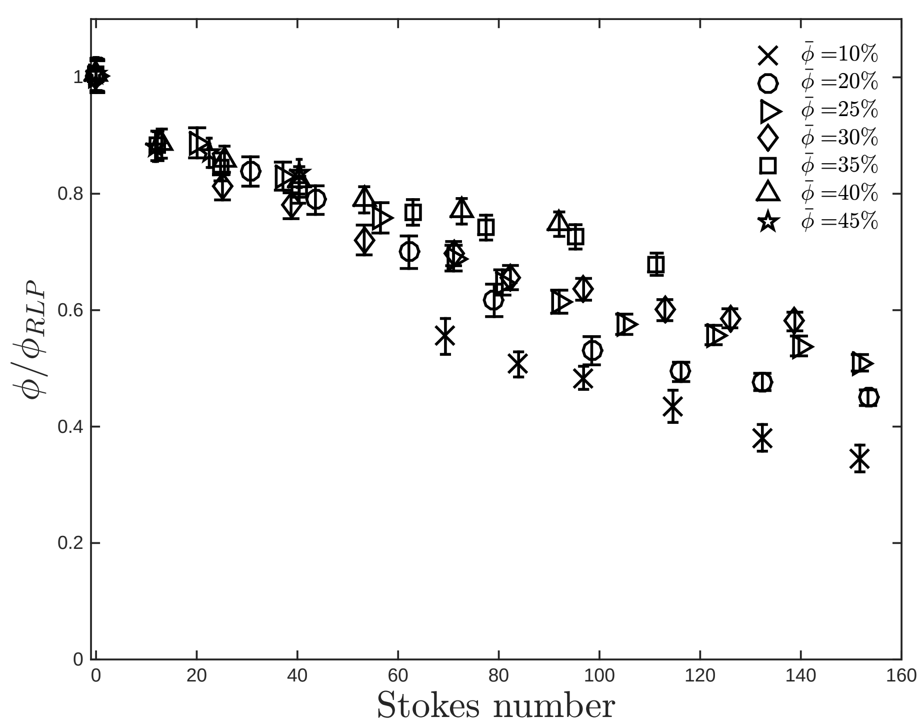

Figure 6.16: Particle packing for different loading volume fractions normalized by the random loose packing as a function of Stokes numbers. The uncertainties in measuring the particle packing are combined in root mean square sense and are represented by the error bars.

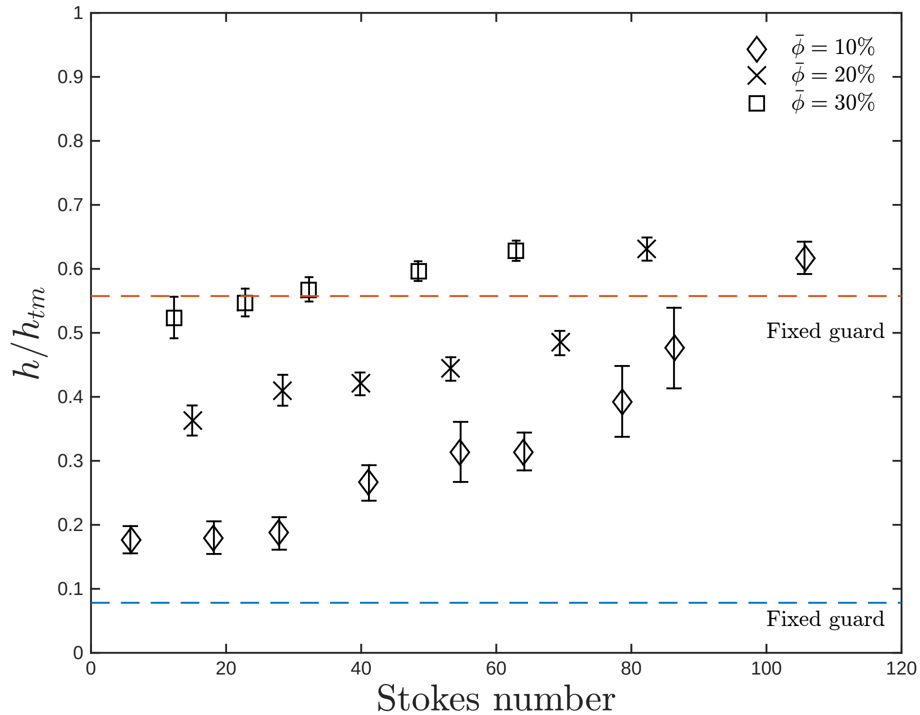

Figure 6.17: Resuspension height normalized by the modified annulus height (h_{tm}) as a function of Stokes numbers. The height of the particles column is measured from the surface of the porous medium. The error bars correspond to the standard deviation of the height measurements.

experiments without a porous medium. Figure 6.18 shows this comparison. The normalized heights for the experiments with porous medium do not seem to follow the same expansion exhibited for the experiments with the same loading fraction but without porous medium . For the case with flow with no porous medium, the expansion at low loading fractions occurs in a more pronounced way than the expansion for the same loading fraction but with porous medium at the bottom. Figure 6.19 shows the heights for the experiments with porous medium measured from the bottom of the annulus normalized by the total annulus height (h_t). These normalized heights are plotted together with the normalized heights for the case without a porous medium on the bottom. In this way, the portion of the test cylinder that is covered by the particles can be observed as a function of the Stokes numbers. The differences in the expansion of a column with the same height but a different amount of particles can be also analyzed with Figure 6.19. The expansion of the column of particles for the case with porous medium on the bottom and $\bar{\phi} = 10\%$ coincides with the expansion measured for a $\bar{\phi} = 20\%$ and no porous medium. Similarly, the expansion of $\bar{\phi} = 20$ and 30% for flow over porous medium compares favorably with the expansion of $\bar{\phi} = 25$ and 30% without porous medium, respectively. This suggests that the expansion of the particles is determined by the distance from the surface of the column of particles to the top boundary rather than the loading fraction. If the same loading volume fraction is considered, the normalized heights for the case with a porous medium

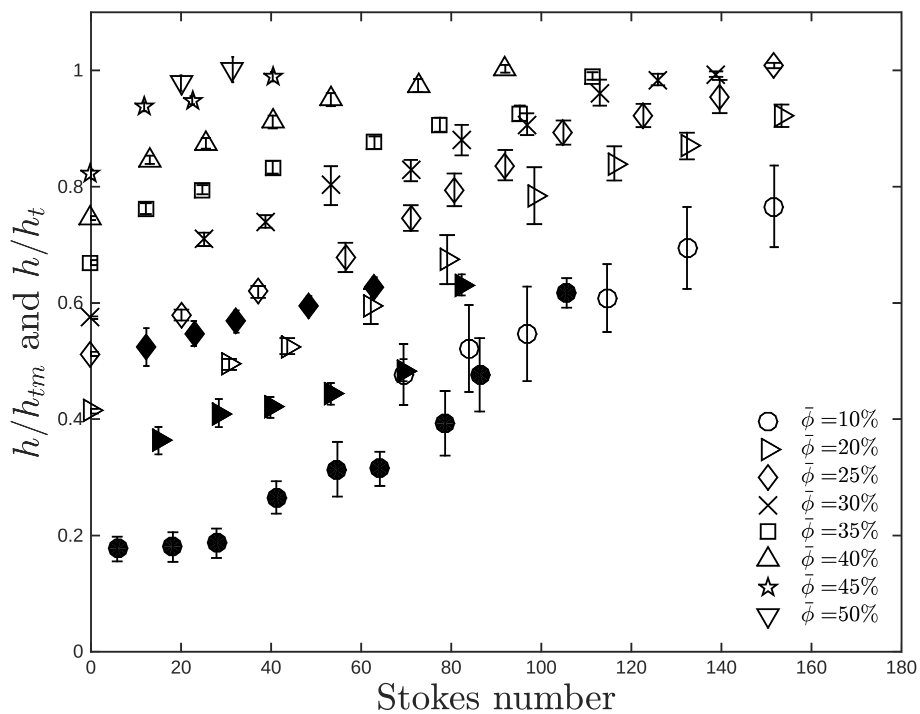

Figure 6.18: Resuspension height normalized by the total modified annulus height (h_{tm} and h_t) for the case with and without porous medium as a function of Stokes numbers. Open symbols correspond to the case with no porous medium on the bottom and close symbols correspond to the case with a porous medium. The heights for the latter case are measured from the top of the porous medium. The error bars correspond to the standard deviation of the height measurements.

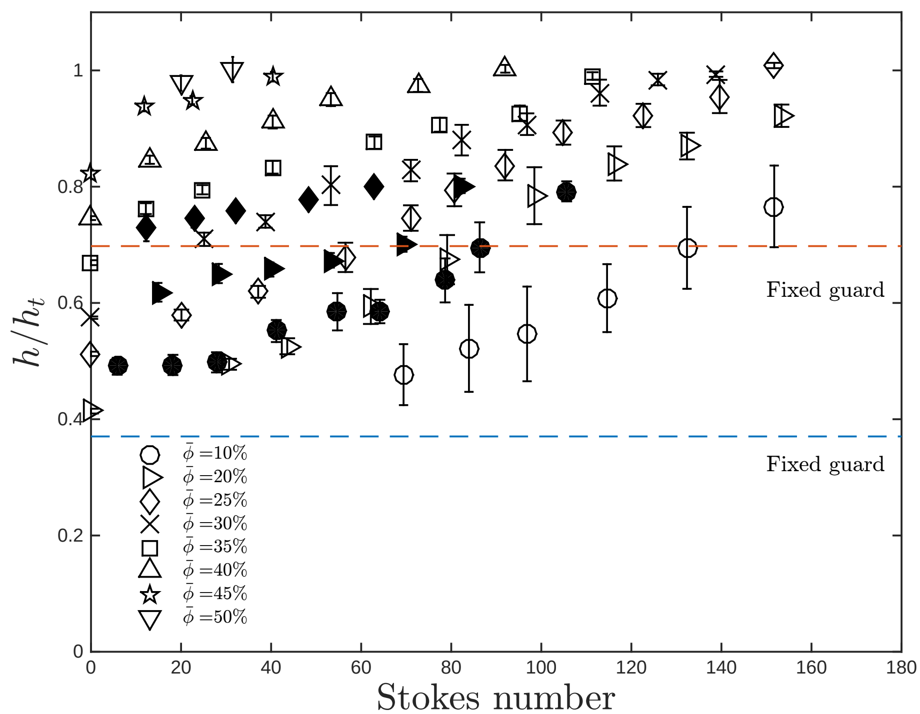

Figure 6.19: Resuspension height normalized by the total annulus height (h_t) as a function of Stokes numbers. Open symbols correspond to the case with no porous medium on the bottom and close symbols correspond to the case with a porous medium on the bottom . For the latter case, the heights shown considered the height of the glass beads layer. The error bars correspond to the standard deviation of the height measurements.

on the bottom coincide with the experiments without the porous medium. Figure 6.20 shows the dependance of the particles packing on the Stokes number for the case of particles fluidized over a porous medium. The dependance on the loading volume fraction is relatively weak compared to the dependance on Stokes number observed for the experiments with no porous medium. The particles' packing data collapses when normalized by the measured random loose packing, as shown in Figure 6.21. The normalized particle packing seems to collapse better than for the case with no porous medium; however, the resuspension of the particles could only be measured for Stokes numbers lower than 100 because of limits on the viewing window.

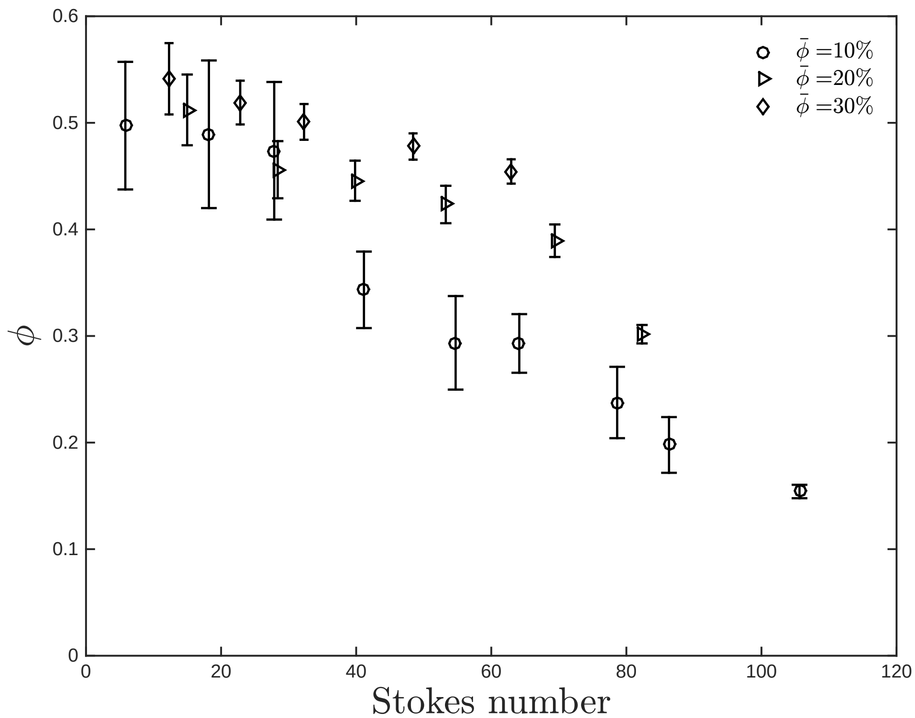

Figure 6.20: Particles packing for different loading volume fractions as a function of Stokes numbers for the case of flow over a porous medium. The uncertainties in measuring the particle packing are combined in root mean square sense and are represented by the error bars.

The packing for porous medium is compared against the packing without a porous medium in Figure 6.22. The normalized particle packing and its dependance on Stokes number for the case of porous and no porous medium on the bottom are shown in Figure 6.23. The particles over a porous medium fluidized less readily as compare with experiments without porous medium on the bottom. However, these differences are not big and both cases seem to follow a similar dependance on the Stokes number.

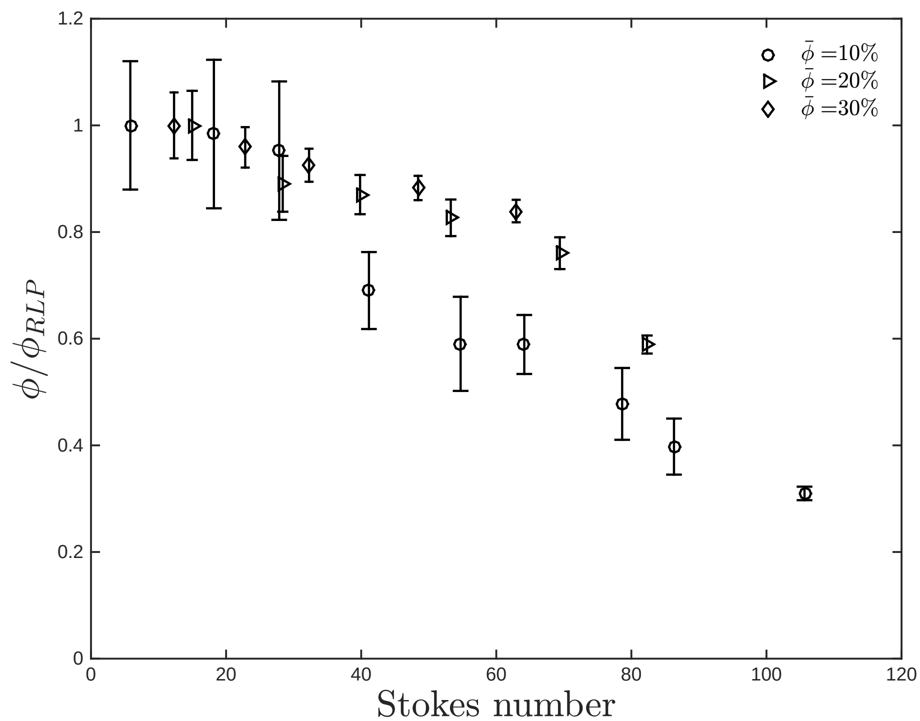

Figure 6.21: Particles packing for different loading volume fractions normalized with the measured random loose packing as a function of Stokes numbers for the case of flow over a porous medium. The uncertainties in measuring the particle packing are combined in root mean square sense and are represented by the error bars.

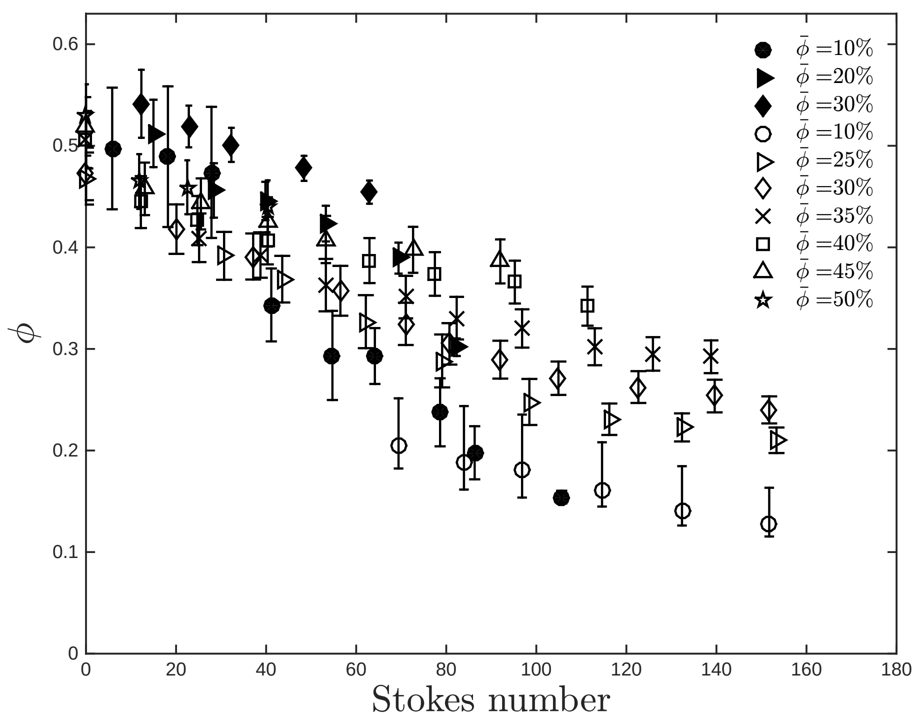

Figure 6.22: Particles packing for different loading volume fractions as a function of Stokes numbers for the case with and without porous medium. Close symbols corresponds to the flow over a porous medium. The uncertainties in measuring the particle packing are combined in root mean square sense and are represented by the error bars.

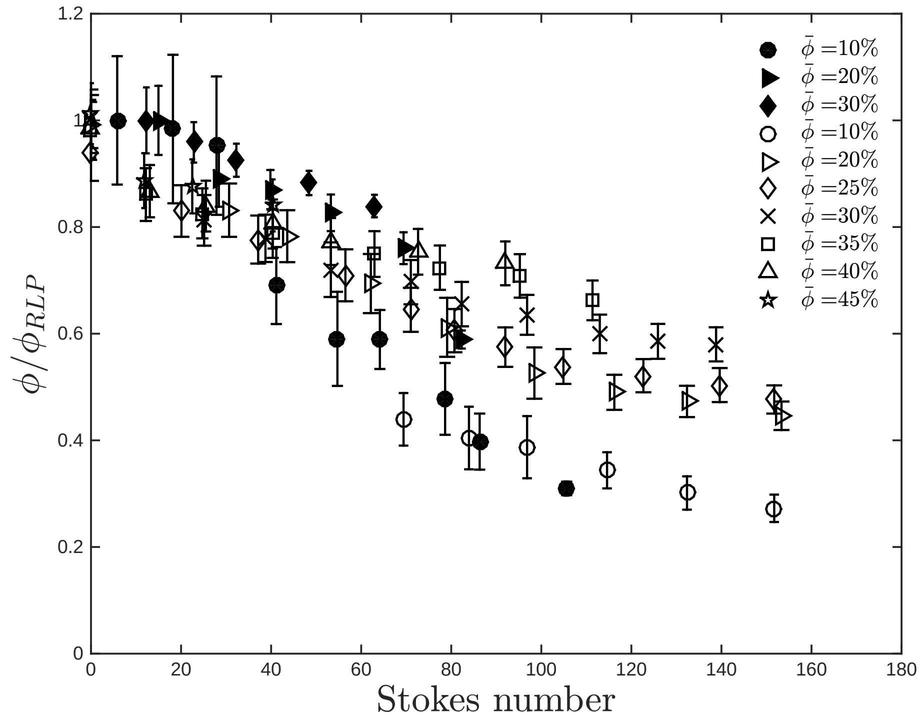

Figure 6.23: Particles packing for different loading volume fractions normalized with the measured random loose packing as a function of Stokes numbers for the case of flow over a porous and no porous medium. The uncertainties in measuring the particle packing are combined in root mean square sense and are represented by the error bars.

6.5 Summary

The particle settling process for non neutrally buoyant particles with a density ratio of $\rho_p/\rho = 1.05$ is presented in the first section of this chapter for the case of no porous medium on the bottom. A gradual compaction of the settled particles is found, where the initial height of the settled particles decreases over a period of 15 minutes once the rheometer is brought to a complete stop. The reason for this further packing of the particles is not completely understood but one explanation could be the gradual release of trapped air in the mixture.

Using the measurements of the particles settled height, the random loose packing is calculated and found to depend on the loading volume fraction for the experiments without a porous medium. The reason why the random loose packing is not constant might have to do with the presence of slightly buoyant particles. Lighter particles would cause the column of particles to further expand, leading to a decrease in the random loose packing.

Finally, the resuspension of the particles due to shearing is presented. When the measured heights for the experiments with a flow over a porous medium is normalized with the modified total annulus height, it does not strictly coincide with the experiments without porous medium with the same loading fraction. However, when the height of the column of particles over a porous medium is measured from the bottom of the annulus and normalized with the total annulus height, it coincides with the normalized measured height for the experiments without porous medium but higher loading fractions. This suggests that the fluidization of the column of particles depend on the position of the particle column or equivalently on the length of the column of liquid on top of that column. The particles resuspension is characterized by measuring the packing of the particles for different Stokes numbers. The particles' packing decreases with the Stokes number for both cases of porous and non-porous medium on the bottom, and if normalized with the measured random loose packing, the resuspension data collapses and follows a single trend where the largest scatter occurs for the highest Stokes number.