Tracer Behaviour under Microgravity and Terrestrial Conditions

1 Introduction

Of industrial and technological importance is the transportation of 'particles' within another medium, be it a fluid as in sewage transportation, or air, as in making 'the perfect potato chip'.
In most cases, the 'particles' are quite a bit larger than tracer and often less than uniform in shape. The main points of interest in this field of research are therefore often to accurately describe the drag and lift forces for optimal transportation for a wide range of specimen of particles, as well as in some cases how to avoid excessive collision forces (No one wants to eat tiny potato chip pieces) or how to increase them for mixing of several particle species or media.
Many academic and industrial investigations about the behaviour of particles in fluid are based on the description of sedimentation, solid fuel and spray transport. These investigations produced several models describing the motion/transportation of single particles and particle clouds in gaseous and liquid fluids. Other fields deal with sedimentation or separation of medium and materials transported within. Again, while this is of great technological importance, the exact behaviour of said particles is of little to no concern other than the rate of separation for a given specimen. Also, these cases usually deal with a high concentration of particles, which is unwanted in the case of tracer particles for flow investigations.
Many techniques for the investigation of flow behaviour and fluid velocity rely on the presence of particles in the flow. These should not only follow the flow velocity and fluctuations accurately, but should also be sufficient in number to provide the desired temporal and in case of 2D or even 3D measurements also spatial resolution. Furthermore, it is highly desirable that these tracer particles are also good light scattering centres, as this improves the signal quality for a given amount of incident (laser) light power.
For camera based measurement techniques, the obtained particle image intensity and the contrast of images is directly proportional to the power of the scattered light. Here, it is often more effective and economical to increase the image intensity by properly choosing the scattering tracer particles than by increasing the illuminating laser power (density).
The light scattered by small particles is a function of many factors, such as the ratio of the refractive index of the particles to that of surrounding medium, particle size, shape, orientation and angle of observation. For spherical particles with diameters larger than the wavelength of the illuminating light, the intensity of the scattered light by the particle can be estimated by Mie's scattering theory [5].

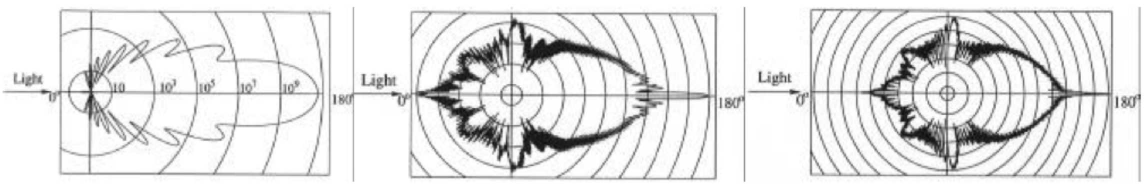

Figure 1.1: Light scattering by glass particles of 1 μm, 10 μm and 30 μm in water [13].

From figure 1.1 one can see that the scattered light intensity increases as the particle diameter increases. It should also be noted that the scattered light intensity is not blocked by the tracer particle but spread out in all directions. Therefore, for a large number of particles inside the light sheet, massive scattering will occur.

The scattering efficiency of the trace particle also strongly depends on the ratio of the refractive index of the particle to that of the fluid. Such as, the refractive index of water is considerably larger than that of air. The scattering of particles in air is at least one order of magnitude more powerful than particles of the same size in water [13]. This is another reason why larger particles have to be used for water flow experiment, which can mostly be accepted since the density matching of particles and fluid is usually better than that in air. However, for flow investigations, it is not only common, but good practice to investigate the scattering performance of tracer particles empirically. For this reason, we will not go into any detail about scattering characteristics of particles of varying materials of a certain size used as scattering centres for laser light with a given wavelength, but refer instead here to the literature [12, 11, 9, 1, 10, 5]
In any case, the fact that flow tracking demands small particles, while light scattering improves with increasing particle size. For this reason, the ability of particles to track the flow and efficiently scatter light are the two most important issues involved in the choice of tracer particles. Since the tracking ability must be fulfilled, the light scattering can be influenced by the particle substance, the incident laser light power, the collection aperture of the light gathering optics and its position, and the light 'detector' and related electronics. For a given flow characteristic often a compromise has to be found. In some cases it might it may also be advantageous to work with different wavelengths, so that e.g. different measurement techniques can be used or different regions or even phases in a two- or multi-phase flow of a flow can be investigated simultaneously.
Some of the best suited particles for laser based measurement techniques like LDV, PTV, PIV etc. such as polymers, hollow SiO_2 micro-ballons or metal coated (hollow) glass spheres, are quite complex to fabricate but are commercially available in large quantities and often at reasonable costs, which makes them well suited to closed loop systems.
However, when larger quantities of particles are required, e.g. for large water or wind tunnels or open loop system, even more economical and/or environment friendly solutions are sought. Here, dedicated particle generators offer a good solution, some of which are also commercially available. Particle generation can be divided according to solid and liquid particles. Solid particles or powders are used to seed liquid flows or in applications such as combustion, where liquid droplets would evaporate. In either case a mono-dispersed size distribution and a spherical particle shape are desirable for most measurement techniques, the later condition being automatically fulfilled with small liquid droplets.
Other tracer particle characteristics are usually specific to the application, the medium, or the measurement technique(s) used: This includes the long-term stability within the medium, their ability to withstand the experiment temperatures in case of the investigation of combustion related experiment, the lack of agglomeration forming etc.
For air flows the evaporation of liquid droplets as seed particles and thus the droplet lifetime in a flow, often determines where the particles should be introduced into the flow, which in turn can influence concentration and uniformity of particle distribution. Although droplet evaporation can be computed for a given relative velocity with respect to the flow, this aspect – as many others – is usually handled empirically, through trial and error.
In combustion systems, such as burners, engines, turbines etc., either the burning or other chemical transformation characteristic or resistance to such of tracer particles may become important. Finally, one should also consider the toxicity of particles used, since there exists a number of excellent light scattering substances, which unfortunately are highly toxic.

2 Choosing tracer particles

The starting point and basic problem associated with all tracer-based optical velocity measurement techniques in fluid mechanics is the reproducible generation of sufficiently monodisperse particles with an appropriate size, shape and density such that they follow the macroscopic flow motion faithfully without disturbing the flow or fluid properties. Once the prime criteria – density and particle size, respectively light scattering efficiency – are met, the choice and selection of tracer particles is often – at least under terrestrial and especially laboratory conditions – done empirically, i.e. by trial and error. The final choice is often made by practical considerations like availability, price, ease of handling etc. and not from theoretical considerations.

2.1 Flow specific requirements

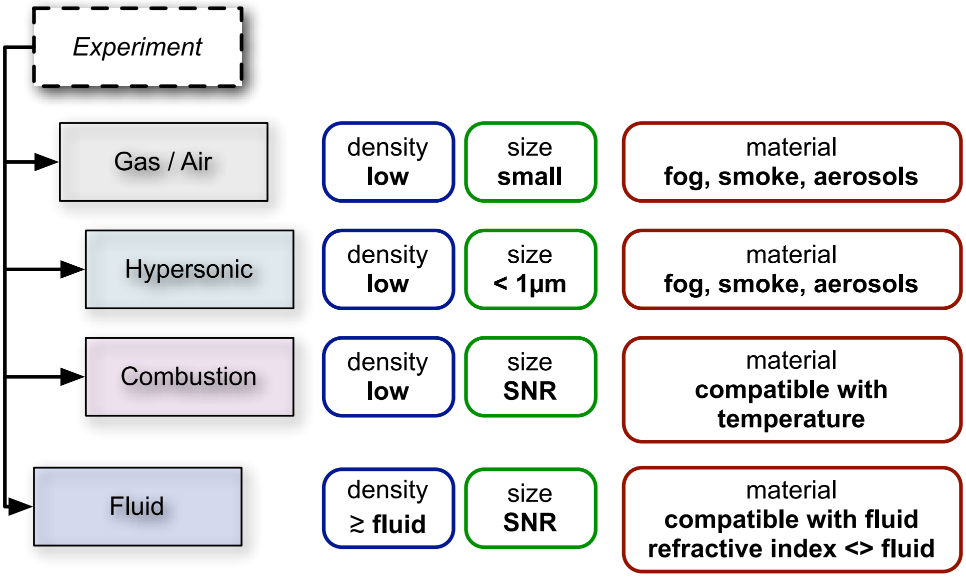

Figure 2.1: Overview of general selection criteria for tracer for different kind of flows

2.1.1 Fluid Flows

In terms of tracking of the flow, i.e. minimal slip between tracer and medium, as well as particle response to turbulence, velocity fluctuations, shocks etc., a particle density closely matched to that of the flow medium is advantageous. This allows much larger particles to be used, thus increasing the light scattered and improving signal quality. The particles in these experiments are usually chosen to have nearly neutral density for optimal tracking response. For this reason, the most important criteria for the tracer selection for fluid flows is the density of the fluid and a close match with the density of the tracer particles. Since both will have different temperature dependencies, a perfect match for a wide temperature range will not be possible.
Together with the slightly heavier, but chemically more stable (silver coated) hollow glas spheres, polyamid (PA) particles have become a staple of flow research in water, silicon oils and other fluids with similar density. There is a wide variety of polymers, whose density is at least close to many typical fluid densities. They are also available in a wide selection of sizes, with an almost monodisperse particle size range.

In large water tunnel facilities, 'natural' tracers like dust, dirt etc. are already available in sufficient quantities to allow precise measurements, and in this way foregoing the need of seeding the flow with tracers altogether.

2.1.2 Air and Gas Flows

For the investigation of air and sometimes also gas flows smoke generators, which deliver condensed oil vapor, or air-operated aerosol atomizers, have been widely and successfully used as these devices easily produce the particle concentrations required for high-resolution measurements in large wind tunnels. Careful attention has been paid to the observation that the particle size distribution generated may strongly deviate from the desired distribution when the liquid level in the generator changes, the pressure varies, or the nozzle holes are contaminated for any reason [2]. This may cause serious problems, especially for investigations with strong vortices or transonic flows with shocks [7].
For seeding in gas flows tracers with particle diameters near or below 1 μm should be used, consistent with the requirements for particles with a high density ratios. A consequence of the small particle size is the need for a high laser pulse energy, in most cases 100 mJ/pulse or more, depending on the size of the light sheet and the particle/droplet size used.

2.1.3 Transsonic and Hypersonic Flows

A special case are transonic and hypersonic flows. When particles traverse through the normal or oblique shocks. Here, the relative velocity to the flow can increase beyond the point at which Stoke's drag is valid and furthermore, the velocity field may be highly rarefied.
Furthermore, seeding of the flow and especially the boundary layer over e.g. an airfoil, is very difficult as any macroscopic particles tend to be removed from these areas by the flow itself. For this reason, tracer particles are not often used with these flows and alternative measurement techniques are used or have been developed for their investigation.

2.1.4 Flows with Combustion and in Turbomachinery

The high temperatures encountered in these flows preclude the use of standard water, oil droplets or the use of materials like polymers or even glass for tracers. The standard tracer types of choice here are TiO_2 or Al_2O_3 particles, which can easily withstand the temperatures, have high scattering efficiencies, are commercially available in a variety of particle sizes and have spherical shape. Ceramic materials such as Al_2O_3, TiO_2 and ZrO_2 are favoured for seeding flames and high-temperature flows and also offer the advantage of a high refractive index, although their dispersion in a gas flow (like that of other powders) can be difficult. Slightly larger seeding particles are often used in combustion experiments, nonetheless they are capable of tracking turbulence frequencies up to nearly 1 kHz.

2.1.5 Microfluidics

Many of the tracers used in 'normal' fluid flows have (and in some cases still are) used also for the investigation of flows in micro-channels. However, as their size is often no longer 'negligible' small compared to the dimensions of the flow under investigations, both new kinds of tracers have been developed, as well as the use of 'particle-less' or 'virtual' tracers has been investigated.

3 Using tracers in space experiments

3.1 Introduction

It is only natural that most of the attention in flow research – or any other research – is drawn to the actual area of interest, that is where the 'real' experiment takes place. In flow research this is usually some sort of device or cell, where the flow can be investigated in detail by the measurement technique(s) of choice. This works fine in a laboratory setting, where the surrounding and necessary auxiliary devices have already been set-up and can be easily cleaned, optimised or – when and where necessary – replaced. However, this is not the case when preparing an experiment for microgravity. Here, each and every piece of the experimental set-up is its own, unique experiment and should be treated as such wherever possible. Things that are very simple to realise in the lab, like taking a fluid out of a tank or similar reservoir, can become their very own research project. Fortunately, many of these effects can nowadays be modelled 'well enough' for design purposes *if* one is aware of (and modelling) all the effects that influence the fluid behaviour in presence (for lab use) and absence (under microgravity) of gravity. However, given that tracers by their very nature are only used in (very) dilute suspensions, which – by design – should not and in reality hardly influence fluid properties like density, viscosity or surface tension, simulating their behaviour is not only difficult but also seen as unnecessary.
While this is true for the actual fluid behaviour, this might not be close enough to the truth in reality when it comes to observed tracer behaviour. And unfortunately, many measurement techniques do not actually observe the fluid flow directly but indirectly by the movement of these tracers, hence their sole reason to be included in the fluid in the first place.
The good news here is however, that many of the effects that can prove (and in some cases already have proven) to be troublesome can be investigated in the lab, by simple experiments without resorting to special test equipment and/or test facilities.
In the following sections we will investigate the various effects to be taken into account for typical operations and/or conditions encountered when conducting flow research under microgravity.

3.2 Storage

While it would be nice to have easy access to ones experiment in space, this simply is not the case, not even for experiments onboard the International Space Station (ISS) or the space shuttle. Even 'last minute access' before launch is hardly ever the case, so that most (if not all) experiments will go at one point or other through a phase of 'storage', that is at rest, without power and/or inaccessible for an extended period of time. This can be minutes to hours in case of an easy-access facility like a drop-tower, to hours if not days in case of sounding rockets, to weeks if not months for experiment to go onto the space shuttle or the ISS.
Starting up an experiment again after a pause (sometimes as short as a lunch break, certainly after weeks or month of disuse) will require some extra effort even in the laboratory, like operating the experiment at a high flow rate for a few minutes, re-furbishing the fluid/tracer mix etc.
The effects to watch out for are sedimentation, adhesion to walls and other surfaces and agglomeration mostly due to sedimentation and respective increase of particle concentration.

3.3 Launch

It is easy to be misled by the extreme accelerations during launch in the thrust direction to believe that this increase of g-forces is likely to have the most severe effect on tracers within the fluid. While such macro-g conditions can lead to accelerated sedimentation rates in case of a mismatch of specific gravity between the tracers and the fluid, this in itself is rarely a cause of trouble, as the lateral forces will stir and shake the fluid so much as to prevent any sedimentation in the first place to happen. However, these lateral forces can introduce by mixing not only gas/air into the liquid phase, where it often disperses until the liquid is saturated, but due to the presence of vanes, baffles, edges etc. inside tanks, pumps or even the experiment cell can stir the tracers in the liquid to the point that they start to agglomerate. Once this process is started, the size of the agglomerates will increase until breakage of the large 'flocs' is equal to their creation. Worst of all, this process – once started – is often *irreversible!*, i.e. once the tracers have aggregated into large flocs, they will not easily break apart again, not even by force, much less on their own. With respect to tracer behaviour, the effects to beware off are extreme shear flows and respectively turbulent and (to a lesser extent) gravitational agglomeration.
The launch environment is in many respects completely different from the actual 'operational' microgravity environment, or even the laboratory one. This is certainly true for momentum management of 'freely' sloshing fluids within the experiment, which definitely should in be avoided if at all possible, but also for the types of flows that can establish during this phase, as well as during de-spin and/or de-tumble of the spacecraft, respectively the experiment. What is more, since the flows are likely to be highly turbulent during this phase, simulation of the effects will be difficult at best.

3.4 De-spin and de-tumbling

While less of a concern for experiments of well controlled flights like droptower capsules, non-floating parabolic flights or manned spacecrafts or even fully stabilised sounding rockets (e.g. Maxus), experiments on spin-stabilised sounding rockets like Texus or Maser will undergo a sharp lateral deceleration during de-spinning, i.e. shortly before the actual microgravity phase and the experiment begins. For example, a Texus sounding rockets (and the experiment inside) rotates at about 4 Hz, and is brought to zero spin within less than half a second by the release of 'jo-jo'-masses. Since this happens right before the start of the microgravity phase of the flight, the experiment is likely to be designed to remove any movement from the fluid within its containment as well, e.g. by the help of vanes etc. However, this will introduce extreme shear flows within the fluid itself, which in turn can lead to agglomeration of the tracers, as e.g. observed on Texus 41 and Texus EML 1 in the capillary channel flow experiment.
Since fluid momentum management is paramount for successfully conducting flow research in microgravity, the question here is how to avoid aggregation of tracers: One solution to this problem is to introduce tracers into the main body of the fluid only after microgravity conditions have been reached. However, as all flows then are likely to be laminar, this approach directly leads to the question how to successfully seed the flow uniformly and with the desired concentration of tracers per unit volume. Not an easy task without some mixing force or mechanism, which in turn would again disturb the flow. Therefore, a better solution is to seek ways for either using tracers, which do not tend to agglomerate even under these conditions, or preventing the selected tracer particles from building aggregates, e.g. by coating the particles with surfactants.

3.5 Experiment operation in microgravity

The absence of a single force – gravity – from all the other forces acting on the fluid (and the tracers within) might seem trivial from the point of view of experiment design or choice of measurement technique and related to that tracer particles. However, as gravity has a dominant effect on many 'typical' flow behaviours on Earth and in the lab, its absence can lead to surprising 'side-effects' to the unwary or anyone too focused on studying 'just' the flow within the experiment area, without taking a 'holistic' view on all aspects of the experiment.
Taking gravity out of the equation shifts the balances of forces governing the behaviour of the flow. Here, the actual influence on tracer behaviour is – for tracers with a specific gravity (nearly) equal to one – almost negligible. Not exactly the result one would expect from the long history of trouble and (near) failures related to the use of tracers in microgravity flow experiments.
However, most of these problems are due to lack of understanding and/or proper investigation of effects before there is microgravity, as well as the assumption that because there is a lack of effects due microgravity, i.e. the absence of gravity, there is a lack of effects due to its presence. This misunderstanding is promoted by the fact that we are so used to those in laboratory research, not to mention in daily life, we take some behaviours for granted, which they are *not*.
As an example, it is common practice to choose tracer particles with slightly large specific gravity, i.e. a density larger than the fluid density. In the lab, with gravity ever present, we will have sedimentation of at least some particles with time. This leads to the build up of a (nearly invisible) and often not recognised 'reservoir' of particles at the 'bottoms' of the experiment, which is not necessarily only the lowest part, but could also be in other regions where flow velocity is low enough to allow the buildup of 'sediments'. Now, if the velocity of the flow is increased in the normal course of the experiment, these 'sedimented' tracers will be slowly re-introduced into the flow. Replenishing the tracers already present and slowly increasing the particle concentration. Here, at higher velocities, these additional tracers provide now improved sampling of the velocity field. Therefore, this is highly desirable!
However, this *will not work* under microgravity! There is no sedimentation. There is no reason, why the particle concentration should be lower at slow fluid velocities and increase with higher. Not taking into account sedimentation in the lab while determining the 'right' concentration for optimal results for microgravity could lead to significant higher concentrations than desired and might reduce measurement accuracy if not even make measurements impossible.
For this reason, some experiments are designed for seeding the flow only after microgravity has been achieved. However, since most flows under investigation are highly laminar, and the experiment design usually strives to minimise any and all disturbances to the flow (at least in the region of interest, this approach has it's own set of troubles: How to get the tracers inside the measurement region, without disturbing the flow to be investigated.
For one thing, there will be no thermal convection to slowly distribute the tracers. Also, capillary forces have negligible effect on tracers inside the flow and surface forces are more likely to introduce unwanted behaviour – like attracting the tracers to windows and other smooth surfaces – then uniformly distribute them through the fluid.
Since researchers strive to investigate the flow not only in the absence of gravitational disturbances, most disturbance generators like pumps, flow meters and other 'mixing' devices are likely to end up on the 'other side' of the experiment area.
However, somehow the tracers need to be uniformly distributed within the fluid before entering into the measurement area.

Achieving the optimal tracer concentration under these conditions can become quite a challenge, especially if no means to *remove* tracers from the flow – if and when required – is incorporated into the experiment design, as well.

3.6 Operation in the laboratory

However, even under normal laboratory conditions this can require some effort in fine-tuning of the seeding. Fortunately, here time is less of an issue and experiments can be 'easily' repeated, at least compared to research under microgravity.

What is more, some parts of the experimental set-up can be investigated just as easily on ground for their compliance with the selected tracer particles, so that they will not cause trouble later on: These are for example, pumps, (mechanical) flowmeters, valves, sliders, windows, tubing etc.

These parts can influence tracer behaviours in many ways. Pumps can not only lead to aggregation due to shear flows, compression and highly turbulent flow within, but particles can also be crushed or compacted. Worse, some pump types might not even allow the particles to pass at all, so that with time they might even slow if not stop the flow through it.

While pumps are often the first suspect for failure, mechanical flow meters are just as easily the cause for the same problems associated with pumps, mainly plugging up the system and stopping the flow, e.g. by aggregating within the flowmeter or causing abrasion if not restricting the movement of the moveable parts. While abrasion might at least allow the flow to continue, though reducing the measurement accuracy, particles in the often extremely tight gaps can stop the flowmeter completely, which for the same reason, would then also stop the flow through it. This in turn, would lead to a (near) total stop of the flow and a major failure for the experiment.

Similar problems can also occur with valves and sliders, especially when they are opened and closed repeatedly. Particles might clog the more delicate parts and keep them from closing or opening properly. Again, this could become a major mode for failure.

Last but not least, particles can attach themselves to tubing, walls and worst of all windows. This 'fouling' can not only remove many tracers from the flow, but especially for windows, can make observing the flow altogether impossible.

3.7 Use of tracers with common flow measurements techniques

Experimental flow investigations with tracers can be performed in the form of flow visualisation or flow measurement or both. Because flow visualisation provides only qualitative information, this technique has been inherently penalised with respect to other techniques that provide quantitative information about the flow, even though much of the understanding stems from 'simple' flow visualisation. However, a very important aspect to take into account with *any* measurement technique requiring tracer particles, like laser Doppler anemometer (LDA), particle tracking velocimeter (PTV), particle image velocimeter (PIV) etc. is that they not only require tracer particles – preferably in high enough concentration to achieve 'high data rates' – but they in fact only do measure the velocity of said tracer particles, *not* of the flow itself.

The size and the density – to minimise inertia effects due to different particle & fluid density – must therefore be chosen very carefully to ensure that the seed particles follow the flow accurately. While this will generally be the case for laminar flow, and therefore for most flows investigated under microgravity, this can become a crucial criteria for the tracer particle selection for turbulent flows, or flows or investigations that for whichever reason require the tracing of "all" velocity fluctuations.

4 Summary

The ability of a tracer to follow the flow accurately is foremost determined by the *density* of the tracer material. This is due to the fact that any differences in density will result in different behaviour with respect to inertia between fluid and tracer and is not influenced by gravity or its absence under microgravity conditions. For common fluid densities – between 0.9 to 1.8 g/cm^3 – there is a huge selection of materials (mostly plastics) with suitable densities to choose from. For this reason other aspects can usually be met fairly easily as well, and by commercially available powders or materials. If an even more accurate match of density, e.g. with respect to temperature dependence is required, designer tracers using compounded plastic materials can be manufactured easily. Or in the case of hollow glass spheres, those with matching density (or size) can be selected or separated by buoyancy or sedimentation.
The second most important set of properties of a tracer particle are its (optical) *size* and *shape*. A slight mismatch of density will lead to more significant deviations from the flow for larger particles, than for smaller ones. However, it is also obvious, that for optical measurement techniques, and here especially the imaging techniques, brighter, which usually translates into larger, particles will improve the signal-to-noise ratio. The selection criteria here is to use those particles, which for the smallest size, give the highest signal-to-noise ratio (SNR).
In case of different size but equal material, larger particles will provide more light scattering, i.e. a larger signal. In case of different materials, but equal particle size, the material with the greater 'visibility' should be chosen, which usually is determined by the difference in refractive index with respect to the fluid. A notable exception here are particles with incorporated quantum dots. Due to quantum effects, these will provide significantly more signal than one would normally expect for their size, when excited with the right laser wavelength.
Most optical measurement techniques like laser Doppler velocimeter (LDV), particle image velocimeter (PIV), particle tracking velocimeter (PTV), etc. work best with spherical or at least 'round' particles. However, they will still work with oblate or even plate like particles as well, but the contrast or signal shape will be influenced by the orientation of the particle while traversing through the 'measurement volume'. For flow visualisation this change in contrast with orientation when the tracer follows the flow is often even desirable, as it can improve the contrast of structures within the flow tremendously.
Once the density for the fluid, respectively tracer material is determined and optimal particle size, shape and concentration within the fluid for a given measurement and experiment set-up have been established, *compatibility* of the tracers with the fluid, as well as the whole of the experiment set-up and procedure need to be investigated.
Obviously only materials should be chosen, which are safe, i.e. non-toxic, non-flammable, etc., and chemically compatible with each other, that is not dissolve, react or otherwise interact with each other in any undesirable way.

For this reason, we have started a long-term storage and compatibility investigation for typical fluids and tracer and experiment materials within this activity.

While the above is usually more than sufficient for 'normal' and laboratory use of tracers in flow investigations, there are some additional issues to be aware of when doing such experiments in space.

One is the question of how to add – and possibly also how to remove – tracers from the flow, without disturbing the flow. This has to be addressed specifically for any experiment and flow under investigation, and can therefore not addressed here in a general study.
However, unrelated to the experiment itself are the problems associated of getting the experiment into space, i.e. transportation, launch and possibly also spin-up and de-spin for spin-stabilized sounding rockets. These can introduce serious shear flows in the experiment or the tracer containment, which in turn can result in fast and *irreversible* agglomeration!
Fortunately, there are several ways to prevent this. In the absence of steric effects, the stability of colloidal systems – and at the upper end of the size scale in some cases also tracer / fluid dispersions – is determined by the balance of repulsive and attractive forces, which the particles experience as they approach each other. If there is mutual repulsion, then the dispersion will resist flocculation / agglomeration.

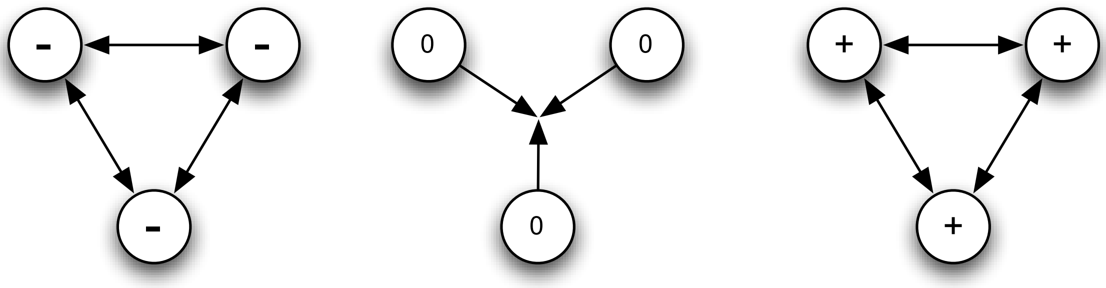

Figure 4.1: Electrostatic forces can stabilize particles suspensions or lead to agglomeration (middle).

If there is no repulsion then the flocculation or coagulation will eventually take place by itself or in case of shear flows (mixing, stirring, pumping, launch, de-spin etc.). As a rule of thumb, particle suspension are stable at room temperature when the electrostatic potential or ζ-potential between the particles is larger than ± 30 mV.
Another way of stabilizing a particle suspension is by attaching chain molecules onto the surfaces, which 'dangle out' into the solution, where they are thermally mobile (like seaweed on the sea floor). On approach of another surface the entropy of confining these dangling chains again results in a repulsive entropic force which, for overlapping polymer molecules, is known as the 'steric' or 'overlap' repulsion.
Various types of adsorptions are possible, depending on the bulk polymer concentration, on whether the polymer is a homopolymer or a copolymer, and on whether the adsorption is via physical forces (physisorption) or by the 'grafting' or 'anchoring' of specific groups via chemical bonds (chemisorption); for further details please refer to [4, 6, 8, 3] etc.

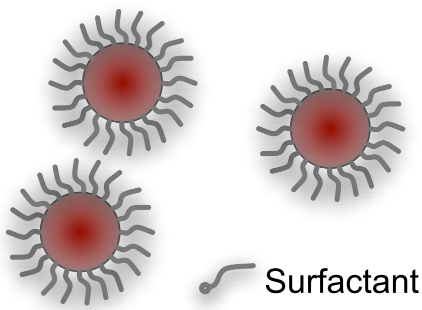

Figure 4.2: Tracers with chain molecules adsorbed / grafted onto particle surfaces.

It is important to understand that for surfactant rich mixtures or when adding 'protectives against coagulation' the order of mixing can effect the stability of the mixture. Here one has to ensure that the surfactants are well adsorbed onto the surface of the particles before adding the tracers into the main fluid.

Recommended Literature

Flow Visualization, Second Edition: Merzkirch, W. (1987); Academic Press, 2 edition.: The book for flow visualization. Gives a good (even if now slightly outdated) introduction to the general use of tracers and related techniques from the perspective of flow *visualization*.

Laser Doppler and Phase Doppler Measurement Techniques: Albrecht, H.-E., Borys, M., and Damaschke, N. (2002); Springer, Berlin.: *The* reference concerning the LDA and PDA technique with many other useful background.

Particle Image Velocimetry: A Practical Guide: Raffel, M., Willert, C. E., Wereley, S. T., and Kompenhans, J. (2007); Springer, 2nd edition: Just what the name says: A very Practical Guide to PIV, also useful for other 'image based' techniques.

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