Reduction of Effective Acceleration to Microgravity Levels

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Introduction

Acceleration due to earth's gravity causes buoyancy driven convection and sedimentation in solutions. In addition, pressure gradients occur as a function of the height within a liquid column. Hence gravity effects both equilbria conditions and phase transitions as a result of hydrostatic pressure gradients. The effect of gravity on the rate of heat and mass transfer in solutal processes can be particularly important in polymer processing due to the high sensitivity of polymeric materials to processing conditions.

The term microgravity has been coined to describe an environment in which the effects of gravitational acceleration are greatly reduced. It may seem odd to talk in terms of reducing the effects of gravitational acceleration since gravitational attraction is a basic property of matter. However, the presence of gravity on in situ processing or measurements can be negated by achieving conditions in which the laboratory, or more specifically, the container of the experimental materials, is subjected to the same acceleration as the materials themselves. With regard to the laboratory reference frame, there is virtually no force on the experimental solutions. This is difficult to achieve, but can be done. A short review of Newtonian physics provides an explanation on both how processes are effected by gravity and how microgravity conditions are achieved.

The fact that fluids deform when subject to a force but solids do not indicates that solids have a structure able to exert an opposing force that negates an externally applied force. Liquids deform when a force is applied, indicating that a liquid structure cannot completely negate an applied force. Just how easily a liquid resists deformation is related to its viscosity. Spaceflight provides an environment in which the laboratory reference frame, i.e. the spacecraft, and all the equipment therein are experiencing virtually identical forces. There is no solid foundation underneath such a laboratory, so the laboratory accelerates according to the force of gravity as do the experimental fluids within the lab. Hence, the magnitude of the forces exerted by the laboratory on the experimental solutions within are greatly reduced. When compared with a laboratory on the ground and averaged over time, the fluids in a spaceflight laboratory experience approximately a 10^{-6} decrease in acceleration relative to their laboratory reference frame, hence the term microgravity.

Experimental

There are several ways to achieve a reduction in the effective acceleration experienced by experiments. All have in common the establishment of conditions in which the laboratory is accelerating due to the force of gravity, but other forces on the lab are absent or insignificant.

Drop Towers. Drop towers are devices in which an experiment package is dropped down a long vertical path. These devices provide a few seconds of free-fall in which the effective acceleration levels on the experiment package are quite small. To ensure that the experiment package drops at a rate consistent with the acceleration due to gravity, air resistance must be eliminated or negated. Some drop towers such as the 5 second drop tower at NASA's Glenn Research Center (GRC) at Cleveland, Ohio, are evacuated of air. Others such as the GRC 2.2 Second Drop Tower use a wake shield that travels just in front of the experiment package, essentially producing a drag free path in front of the package.[1] Another method that has been employed is to use air or gas jets attached to the package to counteract the force of air resistance. The maximum time of reduced acceleration conditions that a drop tower can currently provide is approximately ten seconds. This is provided by a drop tube in a mine shaft in Japan run by the New Energy and Industrial Development Organization. The package falls over a quarter of a mile before breaking commences. The 2.2 second drop tube can perform up to 12 drops per day and can provide an effective acceleration of approximately 10^{-4} g's where g is the acceleration due to earth's gravity at the earth's surface. The 5 second drop tower, known as the Zero Gravity Research Facility can perform 2 drops per day. It provides an effective acceleration level of about 10^{-5} g's.

Parabolic Trajectory Airplane Flights. A plane can reduce the effective acceleration on experiments within by flying a trajectory in which the horizontal component of velocity is constant and the vertical component of velocity is consistent with acceleration due to the force of earth's gravity, i.e.

$$dv_x/dt = 0 \ , \ dv_y/dt = g$$

where v_x and v_y are the horizontal and vertical components of velocity respectively, t is time, and g is the acceleration due to earth's gravity. Integrating these equations twice with respect to time reveals that the trajectory of the plane that satisfies these constraints is a parabola, i.e.

$$x = Ct \ , \ y = (½)gt^2$$

NASA currently uses a KC135 jet often referred to as the vomit comet to fly parabolic trajectories providing an effective acceleration in the payload bay averaging about 10^{-2}g's.[1] The plane can provide about 23 seconds of this acceleration level for each parabola. The plane typically flies about 40 parabolas per day at a cost of around $10,000 for a day of operation.

Spacecraft and Rockets. Spacecraft and rockets provide platforms with longer durations of low effective acceleration. Sounding rockets can provide 5 to 15 minutes of low g. The Space Shuttle can provide up to 17 days and the International Space Station (ISS) can provide months of low g. Average acceleration levels on spacecraft in low earth orbit can be on the order of 10^{-6} g's. There are two sources of acceleration that account for this. One is atmospheric drag, which is on the order of tenths of microg's. The other is the so-called gravity gradient. The acceleration of earth's gravity is

$$A = (Gm_e / r^3)\,\mathbf{r}$$

where A is the acceleration vector, G is the gravitation constant, m_e is the mass of the earth, **r** is the vector to the earth's center, and r is the scalar magnitude of **r**. ∇A varies as a function of orbital position by as much as tenths of a microg/meter. Since the orbital acceleration varies slightly within the spacecraft, the spacecraft exerts a small force on its components to fix them in place within the spacecraft reference frame. This gravity gradient and atmospheric drag account for the micro-g rather than zero-g time-averaged acceleration environment found in a spacecraft. It is interesting to note that r is only about 5% greater in low earth orbit than on the earth's surface. So the absolute value of A is only about 13% less in orbit than on the ground.

Spacecraft are severely constrained experiment carriers. Flights are expensive, few, and far between. Safety considerations are paramount. In addition lead times in preparing for a flight are long. Resources required to perform experiments such as weight, volume, power, video observation time, commanding, crew time for operating an experiment, etc. are all in short supply. Costs of performing experiments on these platforms can be prohibitive. Sounding rockets costs are typically on the order of $100,000 per flight. The use of the Space Shuttle or ISS is largely limited to parasitic use. When shuttle schedules or ISS utilization permits the performance of experiments, they are flown based on the availability of resources such as weight and video. These opportunities are made available only for selected experiments. Experiments in the NASA space program are chosen based on peer review or the level of industrial participation. Industry is allowed to purchase space for proprietary research on a cost prorated basis or less if deemed in NASA's interest.

Limitations of low g platforms. The limited availability of low g platforms, the expense, and other constraints associated with their use are obvious from the previous discussions. A less obvious concern is the complexity of the heat and mass transfer associated with processes performed in these environments. There is a temptation to assume zero acceleration and further assume that all heat and mass transfer is diffusive. Often this is a bad assumption, particularly for the latter case. Frequently, the heat and mass transport occurring in a low-g facility is not easier, but harder to understand than that in the equivalent 1g experiment. Diffusion is typically a slow, inefficient process. Common values for thermal diffusion coefficients in aqueous or organic solutions are on the order of 10^{-3} cm^2/sec. Values for mass diffusivity are on the order of 10^{-5} cm^2/sec or smaller. The associated diffusive velocities over a characteristic distance x are on the order of V = D/x, where V is velocity and D is the diffusion coefficient. Even if the effects of acceleration are dropped six orders of magnitude, the terminal velocity of settling particles may rival the diffusive velocity of interest. Similarly, the reduction in buoyancy driven convection may not be sufficient to reduce this source of heat and mass transfer to levels negligible in comparison with diffusive velocity.

An even more difficult concern involves understanding the effect of vibrations on experiments. In most ground experiments, an investigator can correctly assume that the greatest source of motion in otherwise quiescent experimental solutions arises from the constant acceleration of gravity and that the effects of vibrations are negligible. In low-g facilities, vibrations may be significant drivers of heat and mass transfer. There is a tendency to believe that since the vector average of a vibrational acceleration is zero, the effect on heat and mass transfer is zero. This would be wrong. Although, liquids have a structure that takes time to deform and are somewhat impervious to high frequency vibrations above 10Hz, lower frequencies can mix solutions quite effectively. This is a complex problem involving the frequency of the vibrations, the amplitudes, and the properties of the solutions.

Accelerometers are used to characterize the vibrational levels associated with low-g experiment platforms. One useful analytical tool is to convert acceleration measurements via Fourier transformation into acceleration amplitude vs. frequency charts. Certain features tend to appear consistently in these measurements. Examples include vibrational modes associated with the flexing of laboratory structural components, equipment operations, compressors, fans, etc. The ISS was designed to minimize the effect of vibrations on experiments. Estimates of the effect of vibrations on the mixing of solutions were used to construct the average root mean square (rms) acceleration requirements curve for the ISS shown in **Figure** 1. Typical amplitudes for acceleration on ISS are predicted to reach values greater than 10^{-2} g's in certain frequency ranges. Vibrational accelerations can be mitigated by isolation devices such as the Active Rack Isolation System (ARIS). This device is predicted to reduce the amplitudes of a broad band of vibrational frequencies by one to two orders of magnitude for a broad frequency range.

Acceleration data generated can be used to aid an investigator in understanding the acceleration environment of the experiment. However, this is limited to some degree by the fact that the accelerometer and the experiment are in different locations and experience different environments. Previous data gathered as part of earlier studies can be used to predict the acceleration environment for future experiments, but different experimental equipment and laboratory setup will result in changes that may not be predictable. To mitigate these limitations, optical tools are sometimes employed to aid in characterizing the heat and mass transport in low-g experiments. Still, the experimenter must often be content with creating benchmark materials or data under conditions of low levels of acceleration, the effects of which can only be roughly estimated.

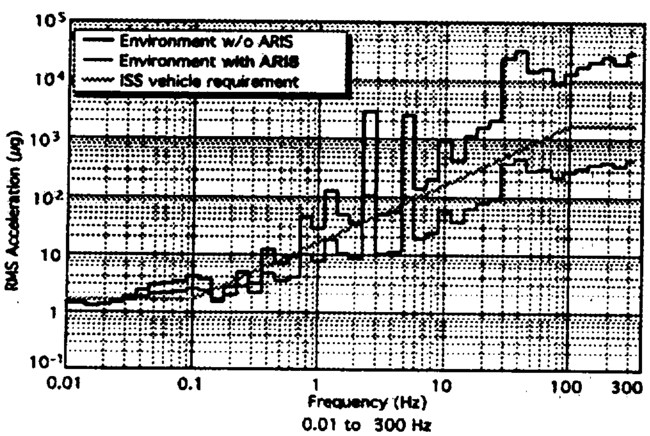

Figure 1. Predicted ISS Microgravity Vibratory Environment.

Discussion

The force of gravity has a profound influence on the processing of materials in solution. Thermal or concentration gradients in solution result in density gradients. This in turn leads to fluid flows effecting heat and mass transport as less dense fluid rises and more dense sinks within the solutions. These flows often convolute or mask other interesting phenomena such as diffusive processes or surface tension driven convection.

Gravity also results in pressure gradients in fluids. The pressure in a fluid is a function of depth. The greater the depth, the more the mass and hence weight of fluid pressing down from above. The resulting increase of pressure with depth is referred to as the pressure head or the hydrostatic pressure. Since pressure is an intrinsic thermodynamic quantity, hydrostatic pressure limits the uniformity of equilibrium conditions in a solution. For example, the critical point in a solution varies as a function of pressure, hence depth within solution.

The effects of gravity typically require investigators to use solid containers when working with fluids. (The use of electrostatic or acoustic levitators is an exception to this.) The presence of a container can have major implications in terms of chemical compatibility concerns, e.g. semiconductor contaminants. Containers also influence the materials produced within, typically effecting properties such as grain structure, polycrystallinity, crystalline orientation, defect density, the degree of undercooling that can be achieved, etc.

Gravity is such a pervasive force that its ramifications on experiments are often not considered since the influence of gravity is perceived to be unavoidable. As a result, laboratory platforms that achieve an effective reduction of acceleration on experiments are often under appreciated. Based on the above arguments it is apparent that the reduction in the effects of acceleration on experiments can be used for studies of diffusive processes, surface tension driven convection, containerless processing of materials, research in the scaling properties of phase transitions, etc. Space Shuttle experiments have been conducted involving each of the above topics.

Relatively few low-g experiments have been performed involving polymeric materials. Even considering the difficulties associated with such experiments this seems odd. One partial explanation for this is that the Space Studies Board of the National Research Council advised NASA, "... the viscous character of most high polymer melts greatly desensitizes their response to gravitational acceleration..."[2] This input has perhaps been interpreted to mean that relatively few experiments involving polymeric materials are of interest. In fact most polymer processes are at a minimum initiated in a relatively low-viscosity state due to the difficulties associated with processing highly entangled melts. In fact polymeric research spans a rich spectrum of viscosity levels often within a single manufacturing process, e.g. the Tromsdorf effect.

High polymer materials are typically entangled and trapped in high energy configurations far from thermodynamic equilibrium. Given this, such materials are highly dependent on the heat and mass transport kinetics associated with their processing. A number of microgravity polymeric experiments have been conducted over the years and it is a goal of this session to provide a platform for their discussion. Another important topic is to stimulate the formulation of new experiments. As the ISS lab facilities will be coming online in the next few years, it is the right timeframe for this activity.

Previous research has found that lowering the effective gravity and presumably the heat and mass transfer associated with this has lead to polymerizations with increased molecular weight and a broader distribution.[3,4] Other polymer research in micro-g includes the study of defect formation in polymer films,[5] and the formation of dispersions.[6] A number of experiments have resulted in crystals of biological macromolecules that diffracted to higher resolution and/or exhibited lower mosaicity.[7] Hopefully with the construction of the ISS this facet of macromolecular research can expand dramatically.

Conclusions

The influence of accelerations applied to experiments relative to the laboratory reference frame cannot be eliminated, but can be greatly reduced by the use of orbiting spacecraft, drop towers, or parabolic trajectory airplane flights. The relative merits of these devices are highly dependent on the experiments of interest. Low effective acceleration can be useful for experiments in a number of areas including, evaluating the effects of surface tension driven convection, containerless processing of materials, scaling properties associated with phase transitions, and processing under conditions of greatly reduced heat and mass transfer. In some circumstances, convective heat and mass transfer can be reduced such that diffusive transport dominates.

References

(1) See http://www.grc.nasa.gov/Doc/facility.htm for descriptions of the NASA's drop towers and the KC-135.

(2) Microgravity Resource Opportunities for the 1990's, Library of Congress Catalog Number: 94-74623.

(3) Sturm, D.; Muller, R.; Rath, N.J. *Proc. VIII'th Europ.Symp. Mat. Sci. Fluid Microgravity* **1992**, 895.

(4) Avci, D.; Thigpen, K.; Mathias, L.J. *Polymer Preprints* **1996**, 37, 317.

(5) Frazier, D.O.; Hung, R.J.; Paley, M.S.; Long, Y.T. *J. Crystal Growth* **1997**, 173, 172.

(6) Fox, B.H.; Schuster, P.A.; Kilp, T.; Fuh, A.Y.G. *AIAA93-0578* **1993**.

(7) McPherson, A. *Crystallogr. Rev.* **1996**, 6, 157.