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Fluid Physics

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19.1 Introduction

The investigations in fluid physics aim at predicting the new behavior of fluids in space and explaining intriguing observations. Fluids (gas, liquid) are present everywhere, that is why many problems of fluid physics are also discussed in the other fields of research discussed in this Book. Fluid behavior is actually markedly different in the space environment than on Earth. Instead of being submitted to the steady Earth gravitational acceleration, fluids in space have to face low gravity and time-dependent acceleration. Forces, as capillary forces, which are usually small or negligible and are generally ignored on Earth, become dominant and lead to unexpected and counterintuitive behavior. Others, as buoyancy forces, disappear or are greatly reduced, making other processes (diffusion, thermocapillary motion) prevailing on buoyancy-induced convection.

In the following, we give an overview of the main fields of research. More information can be found in the references and books [1–3].

19.2 Supercritical Fluids and Critical Point Phenomena

The critical point is the starting point of a new state for gas and liquids. Here pressure and temperature become high enough such that liquid and gas mix together as a dense gas, a "supercritical fluid". In the vicinity of the critical point, all fluids behave in a similar manner. Studying one fluid enables the properties of all fluids to be deduced, this is the so-called critical point universality. Kenneth G. Wilson got the Nobel Prize in 1982 for this discovery. The study of pure fluids near their critical point and, to a lower extent,

Table 19.1   Main parameters in fluid physics

Number	Definition	Meaning	Others
Capillary	$Ca = \frac{\sigma}{\eta V}$	capillary velocity/ fluid velocity	η: dynamic (shear) viscosity; V: fluid velocity
Peclet	$Pe = \frac{VL}{D}$	fluid velocity/ diffusion	D, diffusion coefficient (thermal or solutal)
Marangoni	$Ma = \frac{\sigma_T \Delta T L}{\eta D}$	surface tension forces/ viscous forces	σ_T, surface tension thermal derivative; ΔT, temperature difference; D, thermal diffusivity; L, characteristic length
Weber	$We = \frac{\rho L V^2}{\sigma}$	inertial energy/ capillary energy	ρ, fluid density

liquid mixtures near their dissolution critical point exhibits several exceptional features: very large compressibility, making fluids become compressed under their own weight on Earth, very large thermal expansion, thus even minute temperature gradients produce large density gradients. The fluid becomes subjected to strong turbulent convective flows even under extremely small temperature difference. Vapor–liquid phase transition is mostly governed by buoyancy, bubbles (or droplets) being convected upward (or downward). When nearing the critical point, the Bond number tends to zero; the closest to the critical point, the largest the influence of gravity.

The large sensitivity of near-critical fluids emphasizes the effects. Then, the utilization of the weightless environment allows data to be obtained very near their critical point. This close vicinity enables several investigations to be made [3–5].

19.2.1 Testing Universality

Pure fluids, binary liquids or polymer blends all belong to the same universality class as the Ising system for the ferromagnetism transition. A number of important properties as susceptibility and specific heat obey, asymptotically close to the critical point, universal scaling laws with universal exponents.

19.2.2 Dynamics of Phase Transition

Domains of one phase nucleate and grow at the expense of the other phase. The process, once buoyancy has been suppressed, has been shown to obey universal master laws.

19.2.3 New Process of Thermalization

The "Piston effect" has been discovered. In a closed sample submitted to a temperature rise or heat flux at a border wall, temperature rises very rapidly due to the adiabatic heating by the expansion (heating) or contraction (cooling) of the thermal boundary layer [3]. In contrast to the critical slowing down of the thermal diffusion, this process is all the more rapid as the critical point is neared, leading to "critical speeding-up" instead. On Earth, this phenomenon competes with buoyancy flows to fasten thermal equilibration.
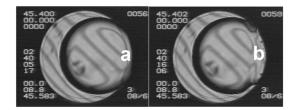
19.2.4 Supercritical Properties

Fluids like oxygen and hydrogen are also used in space under supercritical conditions because they show up as a homogeneous fluid whatever the spacecraft or satellite accelerations are, including the absence of accelerations, and in whatever way the gravity vector is oriented. In addition, supercritical fluids show very interesting environmental properties, for instance, supercritical carbon dioxide is a very powerful (and harmless for health and environment) solvent of organic matter. It is also possible to burn dangerous wastes, like ammunitions, in supercritical water in a very efficient and safe way. Experiments in space have just started in this area [6].

19.3 Heat Transfer, Boiling and Two-Phase Flow

Heat transfer classically uses convection and phase change (condensation, evaporation). In the latter case, two-phase flow (vapor and liquid) occurs. In space, the absence of buoyancy can considerably lower the performances of heat transfer. The investigations into low gravity are then concerned with the mechanisms involved in the process: evaporation, condensation, boiling and two-phase fluid flow.

19.3.1 Two-Phase Flows

Configurations close to an industrial process are mainly considered. A two-phase loop experiment with capillary pumping is used [7]. Capillary forces efficiently pump the liquid in a porous medium, preventing the use of a mechanical device. The basic mechanisms (convection in an evaporating phase, drop evaporation, evaporation in a porous medium) are addressed, together with more technical investigations.

Figure 19.1   Boiling and bubble spreading under zero gravity (SF6, MIR, 1999). (a): $t = 0$, no heat flux at the wall; (b): $t = 11$ s under heat flux, vapor spreads at the contact line location due to the recoil force (from Ref. [9]).

19.3.2 Boiling and Boiling Crisis

Boiling is a highly efficient way to transfer heat. Although boiling has been studied extensively, a basic theory of boiling is still lacking, in particular concerning the phenomena very close to the heating surface. The efficiency of industrial heat exchangers increases with the heat flux. However, there is a limit called critical heat flux. It corresponds to a transition from nucleate boiling (boiling in its usual sense) to film boiling where the heater is covered by a quasi-continuous vapor film and the heat transfer efficiency drops sharply. This transition is called "burnout," "departure from nucleate boiling" or "boiling crisis".

Starting from low-gravity investigations (Figure 19.1), a vapor recoil mechanism for the boiling crisis has been proposed where a fluid molecule leaving the liquid interface causes a recoil force analogous to that created by the gas emitted by a rocket engine. At high enough heat flux, a growing bubble can forcefully push the liquid entirely away from the heating element. The evaporation is particularly strong in the vicinity of the contact line of a bubble, inside the superheated layer of the liquid [8].

19.4 Interfaces

Interfaces play a key role in many areas of science and technology: evaporation, boiling, solidification, crystallization, combustion, foam and thin film drainage, thermocapillary motion, rheology of suspensions and emulsion stability. All these domains benefit from the low-gravity environment.

19.4.1 Liquid Bridges

A liquid bridge is a volume of liquid that is surrounded by another fluid and is attached to more than one solid wall. The most studied bridge [10] is the cylindrical bridge spanning between two coaxial solid disks. Many works

have been devoted to statics (equilibrium shape and stability) and dynamics. In this aspect, one must consider the behavior without thermal effects (disk vibration, rotation, stretching), with thermal gradients (thermocapillary Marangoni flows), diffusion of species (solutal Marangoni flows), phase change (unidirectional solidification—floating zone process), electric and magnetic effects (shape stabilization, convection suppression) and reactive processes (cylindrical flames).

19.4.2 Marangoni Thermo-Solutal-Capillary Flows

Capillary (Marangoni) flows develop when surface tension, σ, varies along the liquid–gas interface, from low surface tension region to high surface tension region [11]. The gradient of surface tension induces a surface flow that tends to drag the underlying bulk liquid with it. The gradient can be induced by a temperature difference, inducing a thermocapillary motion proportional to $d\sigma/dT$, or a difference in concentration, c, of a surface-active species. In this case, the motion is proportional to $d\sigma/dc$. The resulting flow velocity can be large, increasing or diminishing the buoyancy-induced flows on Earth. When liquid droplets or gas bubbles are submitted to a temperature or concentration gradient, the surface flow makes the drop or bubble move, often rapidly.

Such Marangoni flows appear naturally during phase transition where bubbles or drops migrate toward the hottest wall (if $d\sigma/dT > 0$) and convective flows appear on a solid–liquid interface. This is why most of the studies have been performed in configurations close to encountered in material sciences, for example, in the molten zone crystallization process (liquid bridge). There is indeed a direct link between the quality of crystals and the flow properties in the liquid phase. Other investigations are classically concerned with an open tank where the free surface is submitted to a temperature gradient between two parallel rigid walls.

19.4.3 Interfacial Transport

The dynamics aspect of adsorption of soluble surface-active species (surfactants) benefits from the low-gravity environment [12]. Real-time measurements of liquid–liquid and gas–liquid surface tension give a better understanding of the very nature of the interfacial transport process, in particular diffusion in the bulk toward the interface, exchange of matter and dilatational rheology of the interface.

19.4.4 Foams

A liquid foam exhibits a cellular structure made up of gas bubbles surrounded by liquid. The latter is in the form of a thin film wherever two bubbles press tightly together. The foam is not entirely static, unless it has been solidified, for example, polystyrene or metallic foams. As long as the liquid component is present, the foam evolves under the action of three processes. (i) Drainage is the motion of liquid through the foam by gravity. An equilibrium with height is reached, with "dry" foam above and "wet" foam (more than 15% liquid fraction) near the underlying liquid. (ii) Coarsening is the increase with time of the bubble size. This process is due to the diffusion of gas through the thin film as induced by the pressure difference between gas and liquid. Smaller bubbles (larger pressure) are thus eliminated in favor of the larger bubbles (lower pressure). (iii) Rupture. Coarsening ends by the rupture of thin films that causes foam to collapse.

Low-gravity experiments have led to understand the wet foam properties [13]. Some of these experiments, in addition, addressed the quite difficult technology process of metallic foam fabrication without the additives that weaken the materials elaborated on Earth.

19.4.5 Emulsions

Once vigorously shaken, immiscible liquids, like oil and vinegar or oil and water, form a dispersion of small droplets of one liquid in the other phase, that is, an emulsion. The control of the stability of emulsions is one of the most important problems in emulsion science and technology. The main factors are the following: (i) Aggregation. Different droplets of the dispersed phase aggregate in clusters. (ii) Coalescence. Two or more droplets at contact fuse together. (iii) Oswald ripening. The liquid in a small droplet diffuses to a neighboring larger droplet due to the pressure difference corresponding to the different radii of curvature. Although Brownian motion is effective to put very small drops into contact, it is mainly the gravitational forces that eventually "cream" to the surface or "settle" to the bottom.

Experiments in microgravity permit to remove the influence of gravitational forces and highlight the other destabilization causes as the dynamics of surfactant adsorption at the interface, the study of drop–drop interactions and the dynamics of phase inversion in model emulsions (from oil in water to water in oil). Experiments with metallic emulsions have shown that other processes than those described just above, like Marangoni effects, can destabilize emulsions [14].

19.4.6 Giant Fluctuations of Dissolving Interfaces

Large spatial fluctuations in concentration can take place during a free diffusion process, as the one occurring at the interface of liquids undergoing a mixing process [15]. Such fluctuations of concentration (and density) are due to a coupling between velocity and concentration fluctuations in the non-equilibrium state. As the amplitude of the fluctuations is limited by gravity, experiments indeed observe the fluctuations increase ("giant" fluctuations) when gravity is not present. The experiment is performed at the interface between two partially miscible liquids. The observation of such giant fluctuations influences other types of microgravity research, such as the growth of crystals.

19.5 Measurements of Diffusion Properties

In the concept developed by Fick law, diffusion is the tendency of species to spread uniformly in solutions. For a binary liquid solution, a component is always diffusing from high to low concentration points. It is a slow process, for example, it lasts 10^4–10^5 s to homogenize a solution over 1 cm length. When a temperature gradient is present, thermodiffusion—the "Soret effect"—takes place, with typical times on the order of diffusion. These long characteristic times mean that slow convection, as those encountered in Earth-bound measurements, can seriously perturbate the concentration field [16]. High-quality low-gravity measurements eliminate such disturbing motions inside the non-homogeneous samples. Many experiments have been conducted in materials of scientific or industrial interest as molten salts, metallic alloys and organic mixtures. They led to values that are significantly lower than those measured on Earth, leading to discriminate between the many different complex theories that aim at predicting the diffusion behavior. Reliable data are also obtained for the computer industry (solidification, crystallization of materials) and oil companies (diffusion coefficient of crude oils).

19.6 Vibrational and Transient Effects

Most experiments which are performed under space microgravity conditions are selected because of their sensitivity to gravity effects. They are thus also sensitive to acceleration variations that correspond to maneuvers, leading sometimes to unwanted sloshing motions and also to erratic or non-erratic vibrations ("g-jitters").

19.6.1 Transient and Sloshing Motions

During the cutoff or re-ignition phase of a spacecraft engine, or during the orbiting maneuvers of a satellite, the motion of two-phase fluids (e.g., oxygen and hydrogen in equilibrium with their vapor) in the reservoirs can exhibit severe sloshing motion that can even lead to stop the alimentation of the engines. The physics of the problem is complicated by the fact that the liquid-free surface is not simply flat. In addition, when the fluids and the solid mass are comparable in magnitude, the dynamics of the system are coupled [17]. Experiments to validate three-dimensional computational fluid dynamics simulation have been carried out mostly on model fluids, by using scaling with the Bond and Weber numbers, the main numbers involved in the problem. Only very few experiments were performed in real spacecrafts' tanks or with real cryogenic fluids (oxygen, hydrogen).

19.6.2 Vibrational Effects

Knowledge, prediction and minimization of vibration effects are often a necessity when dealing with the control of space experiments. Depending on the vibration amplitude and frequency, the density inhomogeneities (due to thermal gradients or vapor and liquid inclusions) tend to orientate parallel or perpendicular to the vibration direction. Vibrations applied to mechanical systems can induce destabilization or stabilization, depending on the characteristic features of the vibrations (frequency, amplitude) and the direction of vibration with respect to the density gradient orientation. Many equilibrium and non-equilibrium phenomena can then be affected by the presence of high-frequency vibrations.

Vibrations can easily provoke average motions in fluids with density inhomogeneities, counterbalancing or emphasizing the gravitational flows on Earth and inducing in space effects that are similar to those provoked by gravity. In particular, thermal instabilities similar to the one encountered on Earth, as the well-known Rayleigh–Bénard instabilities, can be induced by vibrations [18]. Vibrations can then be of interest for the management of fluids and can be considered as a mean to create an "artificial" gravity in space (see Chapter 15).

A number of investigations have been conducted under weightlessness during phase transition, especially near a vapor–liquid critical point [19]. Thermo-vibrational aspects have been the object of experiments with liquid and liquid solutions [20] to evaluate the effect of vibration on the Soret coefficients (thermodiffusion) and in homogeneous, supercritical fluids near

their critical point where the effects are magnified. Experiments have also been conducted in material science (solidification). They all conclude that vibrations can induce large effects on fluid behavior.

19.7 Biofluids: Microfluidics of Biological Materials

Although the basic constituents of a biological fluid, for example blood, are of the order of micrometers, gravity and its absence can deeply affect the behavior of biofluids [21]. The other length scales (diameter and length of the vessel) are indeed large. Investigations into weightlessness of vesicles, which are good models for blood cells, show that vesicles can undergo temporal oscillations under the influence of shear flow. These studies have also industry relevance as micron-sized particles that are very close to blood compounds (red blood cells, white blood cells) can be separated by a hydrodynamic focusing method (the so-called split technique). Microgravity environment is mandatory to improve the process.

References

[1] Monti, R. *Physics of Fluids in Microgravity*. London and New York: Taylor and Francis, 2001.

[2] Seibert, G. *A World Without Gravity–Research in Space for Health and Industrial Processes*. Noordwijk: ESA Publication Division, 2001.

[3] Zappoli, B., D. Beysens, and Y. Garrabos. "Heat Transfers and Related Effects in Supercritical Fluids." Dordrecht Heidelberg New-York London: Springer, 2015.

[4] Barmatz M., and I. Hahn. "Critical Phenomena in Microgravity: Past, Present, and Future." *Review of Modern Physics* 79 (2007): 1–52.

[5] Shen, B., and P. Zhang. "An Overview of Heat Transfer Near the Liquid-Gas Critical Point Under the Influence of the Piston Effect: Phenomena and Theory." *International Journal of Thermal Sciences* 71 (2013): 1–19.

[6] Pont, G., S. Barde, B. Zappoli, Y. Garrabos, C. Lecoutre, D. Beysens, M. Hicks, U. Hegde, I. Hahn, N. Bergeon, B. Billia, R. Trivedi, and A. Karma. "DECLIC, now and tomorrow." *Proceedings of 64th International Astronautical Congress (IAC)*, Pékin, Chine, (23–27 Sept. 2013), IAC-13,A2,5,5,x19013.

[7] Lebaigue, O., C. Colin, and A. Larue de Tournemine. "Forced Convection Boiling and Condensation of Ammonia in Microgravity." *Annals of [20]*

the Assembly for International Heat Transfer Conference 13 (2006): 250–259.

[8] Nikolayev, V.S., D. Chatain, Y. Garrabos, and D. Beysens. "Experimental Evidence of the Vapour Recoil Mechanism in the Boiling Crisis." *Physical Review Letters* 97 (2006): 184503-1–184503-4.

[9] Garrabos, Y., C. Chabot, R. Wunenburger, J.-P. Delville, and D. Beysens. "Critical Boiling Phenomena Observed in Microgravity." *Journal de Chimie Physique* 96 (1999): 1066–1073.

[10] Martinez, I., and J. Perales. "Mechanical behavior of liquid bridges in microgravity." In *Physics of Fluids in Microgravity*, edited by R. Monti, 21–45. London and New York: Taylor and Francis, 2001.

[11] Castagnolo, D., and R. Monti. "Thermal Marangoni flows." In: *Physics of Fluids in Microgravity*, edited by R. Monti, 78–125, London and New York, NY: Taylor and Francis, 2001.

[12] Passerone, A., L. Liggieri, and F. Ravera. "Interfacial Phenomena." In *Physics of Fluids in Microgravity*, edited by R. Monti, 46–77. London and New York: Taylor and Francis, 2001.

[13] Saint-Jalmes, A., S. Marze, H. Ritacco, D. Langevin, S. Bail, J. Dubail, G. Roux, L. Guingot, L. Tosini, and P. Sung. "Diffusive Liquid Transport in Porous and Elastic Materials: The Case of Foams in Microgravity." *Physical Review Letters* 98 (2007): 058303-1–058303-4.

[14] Miller, R., and L. Liggieri. *Interfacial Rheology*. Leiden: Brill, 2009.

[15] Vailati, A., and M. Giglio. "Giant fluctuations in a free diffusion process." *Nature* 390 (1997): 262–265.

[16] Van Vaerenbergh, S., and J.-C. Legros. In *Physics of Fluids in Microgravity*, edited by R. Monti, 178–216. London and New York: Taylor and Francis, 2001.

[17] Vreeburg, J.P.B., and A.E.P. Veldman. "Transient and sloshing motions in an unsupported container." In *Physics of Fluids in Microgravity*, edited by R. Monti, 293–321. London and New York, NY: Taylor and Francis, 2001.

[18] Gershuni, G.Z., D.V. Lyubimov, "Thermal Vibrational Convection." New York, NY: Wiley, 1998.

[19] Beysens, D., D. Chatain, P. Evesque, and Y. Garrabos. "High Frequency Driven Capillary Flows Speed Up the Gas-Liquid Phase Transition in Zero-Gravity Conditions." *Physical Review letters* 95 (2005): 034502-1–034502-4.

[20] Mialdun, A., I.I. Ryzhkov, D.E. Melnikov, and V. Shevtsova. "Experimental Evidence of Thermovibrational Convection in Low Gravity." *Physical Review Letter* 101 (2008) 084501-1–084501-4.

[21] Mader, M., C. Misbah, and T. Podgorski. "Dynamics and Rheology of Vesicles in a Shear Flow Under Gravity and Micro-Gravity." *Microgravity Science and Technology* 18 (2006): 199–2003.