

NEAR-CRITICAL POINT HYDRODYNAMICS AND MICROGRAVITY

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The critical point of fluids is the termination point of the gas-liquid saturation curve (Fig.1), when gas and liquid phases merge in a unique supercritical “state”. This state exhibits very particular properties. Above the critical temperature and pressure, supercritical fluids exhibit a number of specific properties (large density, low viscosity, large diffusivity), which make them intermediate between liquids and gases [1-2]. In addition, their isothermal compressibility and thermal expansion can become very large, especially when they approach the critical point. The highly variable properties of near-critical fluids make them very attractive for studying many phenomena that hold for all fluids because of the critical universality. On the other hand, supercritical fluids are increasingly used by the food and waste management industry [2] for their solubilization properties (e.g. supercritical CO₂), as host of “cold” combustion (e.g. supercritical water), in energetics (supercritical thermal or nuclear plants), and in astronautics (e.g. storage of cryogenic fluids). However, their behavior under terrestrial (1-g) or space (zero-g) conditions is not so well investigated and their use raises fundamental questions concerning fluid dynamics, heat transfer, interfacial and nucleation phenomena, and chemical processes. Experiments in the absence of gravity-induced effects are often necessary to answer these questions and enhance knowledge in this field.

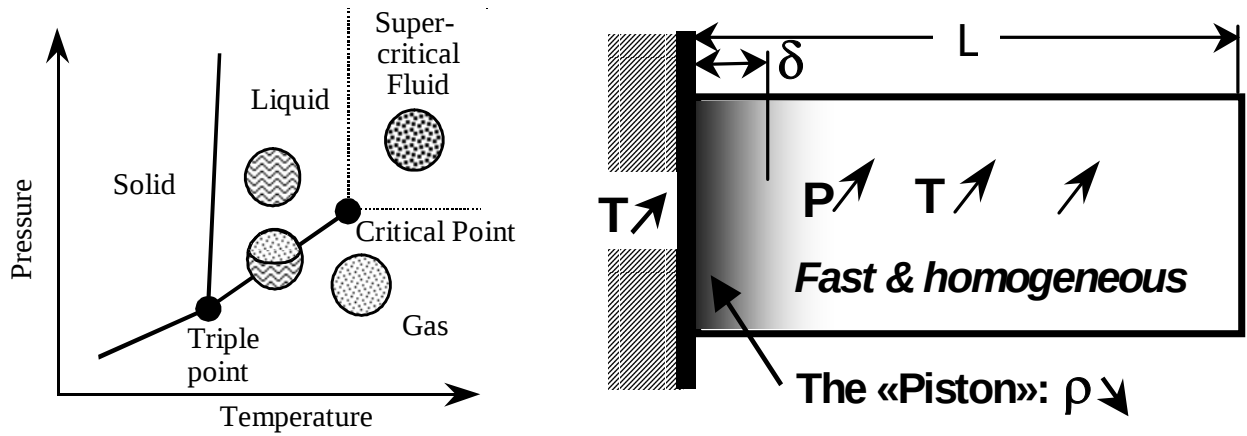


Fig. 1. (a) Phase diagram of a pure substance. (b) The Piston Effect mechanism [3-4]: a thin hot boundary layer expands and compresses the bulk fluid. The corresponding temperature profile shows a thin zone of strong gradients near the heated boundary (thermal boundary layer δ) and a homogeneous rise in the rest of the fluid, that settles at the speed of sound.

Scaling. An important aspect of the critical region is that most of the anomalies in the thermodynamic and transport properties can be set in the form of scaled, universal functions (power laws) with respect to the critical temperature or density. A very important consequence follows, that any results obtained with one fluid can be immediately rescaled to describe any member of a whole class of systems, called a “class of universality”. This class is only defined by the space dimensionality d ($=3$ in normal space) and n ($=1$ for fluids), the ‘order parameter’ dimension.

By enabling measurements to be performed extremely close to the critical point, zero-g experiments have made possible the precise measurements of important, weak power law divergence, such as that of the specific heat at constant volume C_v . From space experiments, the temperature divergence of the specific heat has been determined with a very high precision. With the reduced temperature $\varepsilon = |T - T_c|/T_c$ (T is temperature, T_c is the critical temperature), the specific heat diverges as $C_v \sim \varepsilon^{-\alpha}$ near the critical point. The “critical” exponent α is universal. The value deduced from the space experiments, $\alpha = 0.1105 + 0.025 \pm 0.027$ [5], indeed appears to be very close to the result of the Renormalization Group theory, $\alpha = 0.110 \pm 0.005$.

Thermalization. The thermal diffusivity of fluids vanishes near the critical point and a simple calculation shows that it would need more than one month to reach thermal equilibration in a sample of 1 cm^3 at $T - T_c = 1\text{ mK}$. At the beginning of the microgravity experiments, it thus seemed hopeless to the scientists to try to homogenize in temperature and density a sample of fluid close to the critical point in a reasonable experiment time. However, it appeared that, when heating a sample wall, the hot diffuse boundary layer expanded to compress adiabatically the whole fluid. As a result, a spatially uniform heating of the bulk fluid was observed. We coined this adiabatic heating phenomenon the “Piston effect” (PE). This Piston effect is at the origin of very particular behaviours; one is particularly paradoxical, when the vapor is in equilibrium with liquid below the critical point. While heating the cell, the temperature of the vapor becomes *greater* than that of the wall, seemingly contradicting the laws of thermodynamics [6].

Phase transition. It is a very out of equilibrium process. In a typical experiment, the supercritical fluid is thermally quenched from a region of the phase diagram where it is homogeneous (at temperature T_i) to a region where it is thermodynamically stable as two phases (at temperature T_f).

On earth, the denser phase flow down and the lighter up, in a turbulent way that prevents the underlying mechanisms to be clearly identified. Under weightlessness, growth is only limited by the coalescence of bubbles or droplets that nucleate [7]. When the volume fraction ϕ of the nucleated phase is low, the droplets collide by Brownian motion. The average distance L_m between the drops evolves as $L_m = 2\pi(k_B T / 6\pi\eta)t^{1/3}$ where t is time, η is the shear viscosity, T is absolute temperature and k_B is the Boltzmann constant.

To a given ϕ corresponds a typical interaction length between domains. When $\phi > 0.3$, the flow generated by a coalescence event is able to move a neighboring drop and thus induces other coalescence events [8]. Such a process therefore creates a chain reaction of coalescence. In the viscous limit, the pattern looks interconnected. Growth is limited by the balance between the capillary pressure gradient σ/R (σ is the gas-liquid surface tension) and the friction due to the shear viscosity, so that $L_m = b(\sigma/\eta)t$. Here $b \approx 0.03$ is a universal constant.

The development of domains by coalescence events is very general. The universality of behavior, which is observed in fluids and liquid mixtures, can be extended to others areas of science. In particular, it can be applied to developmental biology [9] where tissues can be considered as very viscous liquids (viscosity $\approx 10^6\text{ Po}$), with a weak surface tension arising from the balance of adhesion sites between the tissue cells (effective interfacial tension $\approx 10\text{ dyn. cm}^{-1}$).

Vibrations. Another situation is concerned with phase transition under an external field that is not gravity. A study of phase separation was performed in H_2 under vibration. Weight was compensated by a volumic magnetic force. It appears that the effect of vibrations is primarily governed by inertial effects that initiate different velocities inside the growing gas and liquid domains. A major result is that the growth is unaffected as long as the domain size is smaller than the viscous boundary layer thickness. When the size is larger, vibrations speeds up phase transition, whatever interconnected or separate bubbles are concerned, and localize the liquid and vapor phases perpendicular to it. The investigations suggest that a periodic excitation can act as a kind of artificial gravity, which speeds up phase transition and localizes the liquid and vapor phases perpendicular to it [10].

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