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Coarsening dynamics / Dynamique de *coarsening*

Coarsening in granular systems

Coarsening dans les systèmes granulaires

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ABSTRACT

We review a few representative examples of granular experiments or models where phase separation, accompanied by domain coarsening, is a relevant phenomenon. We first elucidate the intrinsic non-equilibrium, or athermal, nature of granular media. Thereafter, dilute systems, the so-called "granular gases", are discussed: idealized kinetic models, such as the gas of inelastic hard spheres in the cooling regime, are the optimal playground to study the slow growth of correlated structures, e.g., shear patterns, vortices, and clusters. In fluidized experiments, liquid–gas or solid–gas separations have been observed. In the case of monolayers of particles, phase coexistence and coarsening appear in several different setups, with mechanical or electrostatic energy input. Phenomenological models describe, even quantitatively, several experimental measures, both for the coarsening dynamics and for the dynamic transition between different granular phases. The origin of the underlying bistability is in general related to negative compressibility from granular hydrodynamics computations, even if the understanding of the mechanism is far from complete. A relevant problem, with important industrial applications, is related to the demixing or segregation of mixtures, for instance in rotating tumblers or on horizontally vibrated plates. Finally, the problem of compaction of highly dense granular materials, which is relevant in many practical situations, is usually described in terms of coarsening dynamics: there, bubbles of misaligned grains evaporate, allowing the coalescence of optimally arranged islands and a progressive reduction of the total occupied volume.

RÉSUMÉ

On décrit quelques exemples représentatifs d'expériences et de modèles concernant des matériaux granulaires, dans lesquels apparaît une séparation de phases avec formation de domaines de plus en plus grands (*coarsening*). On précise d'abord la nature intrinsèque des matériaux granulaires hors de l'équilibre, dans lesquels la température n'intervient pas. On discute ensuite les systèmes dilués appelés «gaz granulaires» : des modèles cinétiques idéalisés, tels que des gaz de sphères dures inélastiques en cours de refroidissement, sont l'outil idéal pour étudier la croissance lente de structures corrélées, par exemple des figures de cisaillement, des tourbillons et des amas. Dans des expériences en milieu liquide, on a observé une séparation liquide–gaz ou solide–gaz. Dans le cas de monocouches de

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particules, la coexistence de phase et la croissance des domaines apparaît dans diverses situations, quand on fournit de l'énergie mécanique ou électrostatique. Des modèles phénoménologiques décrivent, au moins qualitativement, divers résultats expérimentaux, concernant la dynamique de *coarsening* aussi bien que la transition dynamique entre les différentes phases granulaires. L'origine de la bistabilité semble liée à une compressibilité négative, révélée par des calculs d'hydrodynamique granulaire, mais le phénomène est loin d'être bien compris. Un problème important, notamment pour ses applications industrielles, est celui de la décomposition des mélanges ou de leur ségrégation, par exemple dans des tambours tournants ou sur des plaques vibrantes horizontales. Enfin, le problème du compactage des matériaux granulaires très denses, qui se pose dans bien des situations pratiques, est ordinairement décrit comme un *coarsening* : des bulles de grains mal alignés s'évaporent, ce qui permet la coalescence des îlots bien disposés et une réduction progressive du volume total occupé.

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1. Introduction

Granular systems are substances made of many *grains*, i.e. particles of average diameter roughly larger than 10^{-2} mm [1]. The size of grains is such that interactions are fairly modeled by dissipative hard core repulsion. Correspondingly, granular systems are athermal, that is they do not posses neither a spontaneous long-term dynamics nor a thermodynamic equilibrium state, except the trivial case of an inert immobile stack (or pile) [2,3].

However, injecting energy, usually by means of vibration, shaking, tumbling or falling, leads the granular system to show a variety of dynamical regimes, i.e. different "phases", roughly analogous to solid, liquid or gas states of molecular matter [4,5]. It is quite hard to push the analogy much forward, since dissipation, in the form of tangential friction and inelastic collisions, makes granular media intrinsically out of equilibrium: in many cases it is evident that not only an Hamiltonian, but even a well-defined thermostat's "temperature" is lacking and therefore no Gibbs distribution can be postulated.

Notwithstanding the inherent non-equilibrium nature of granular phases, many phenomena analogous to equilibrium phase transitions show up in granular experiments and simulations. In most of them, a variation of the input energy flux sensibly changes the internal ordering of the material. Sometimes, the transition from disordered to ordered phase is associated with a growth in time of the size of ordered domains, similarly to what happens in more standard coarsening phenomena. In this case, an abrupt change of the energy input rate plays the role of the usual quench in coarsening dynamics. In this short review, we collect some noticeable examples where the concept of coarsening is empirically meaningful for interpreting and understanding results in the framework of granular systems. For a more extensive review of patterns and collective behavior in granular media, please refer to [6].

The presentation follows a decreasing energy line. In Section 2, we address the more dilute models, i.e. the so-called granular gases, which in the cooling regime display instabilities toward non-homogeneous states with growing domains in the density and velocity fields. Section 3 concerns experiments with dilute or moderately dense shaken granular materials, where several kinds of phase separation appear, with ordered domains that slowly grow in time. The instructive case of electrostatically driven granular fluids is described, with a few noteworthy examples. In Section 4, we discuss the case of demixing or segregation, which usually applies to dense granular materials, slowly agitated or rotated in drums. In Section 5, the compaction dynamics, which is often interpreted as an evaporation of alignment defects or a coarsening of aligned domains, is briefly reviewed. Finally, the last section draws conclusions and perspectives.

2. Cooling granular gases

Fluidization of granular media is achieved by injecting mechanical energy into the system, typically by shaking the whole container or vibrating one of its sides [2]. When the packing fraction ϕ is low enough (typically lower than 50%), a gas-like or liquid-like stationary state is rapidly achieved, characterized by a "granular temperature", which is defined as $T_g = \frac{1}{d} m \langle v^2 \rangle$ where d is the dimensionality, m the mass of a grain and v^2 the squared modulus of its vectorial velocity. The granular temperature is determined by a balance between the energy injected and the dissipation in collisions, which is usually parameterized by a restitution coefficient $\alpha \leq 1$ ($\alpha = 1$ for elastic collisions). Several examples of "phase transitions" have been recognized in fluidized granular systems. In the absence of an interaction energy scale, due to the hard-core nature of the grain–grain collisions, the transition is usually controlled by the packing fraction, or by the restitution coefficient, rather than the granular temperature. A relevant exception is constituted by the sudden quench protocol, where the fluidizing mechanism is abruptly interrupted and a "cooling" regime intervenes. In this cooling regime, typically studied in simulations and within kinetic theory [3], the growth of ordered structures in the velocity field (vortices or shear bands) and in the density field (clustering) is observed [7]. In kinetic theory, the idealized starting point is the so-called Homogeneous Cooling State (HCS), which is a spatially homogeneous solution of the inelastic Boltzmann equation where the temperature follows the Haff's law, i.e. asymptotically $T_g(t) \sim t^{-2}$. Granular Hydrodynamics (GH) [8], which is expected