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Solid components separation from heterogeneous mixtures through turbulence control

Valentin Nedeff [a], Gabriel Lazar [a,*], Maricel Agop [b,c,**], Lucian Eva [d], Lacramioara Ochiuz [e,*], Dan Dimitriu [f], Lucia Vrajitoriu [f], Cristina Popa [g]

[a] Vasile Alecsandri University of Bacau, Faculty of Engineering, 157 Marasesti Str., 600115 Bacău, Romania
[b] Physics Department, Faculty of Machine Manufacturing and Industrial Management, Gheorghe Asachi Technical University, 59A Prof. dr. docent Dimitrie Mangeron Blvd., 700050 Iasi, Romania
[c] Lasers, Atoms and Molecules Physics Laboratory, University of Science and Technology, Villeneuve d'Ascq, 59655 Lille, France
[d] Emergency Clinical Hospital Prof. Dr. Nicolae Oblu, Ateneului Str. 2, 700309 Iaşi, Romania
[e] Faculty of Pharmacy, Department of Pharmaceutical Technology, University of Medicine and Pharmacy Gr. T. Popa, 16 University Str., 70015 Iaşi, Romania
[f] Faculty of Physics, Alexandru Ioan Cuza University, 11 Carol I Blvd., 700506 Iasi, Romania
[g] Dentistry Department, University of Medicine and Pharmacy Gr. T. Popa University, 16 University Str., 70015 Iaşi, Romania

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ABSTRACT

Assuming that the particle movements of fluid–solid mixture occur along continuous but non-differentiable curves, in the framework of scale relativity, the separation processes of the solid components from heterogeneous mixtures are analysed. By means of a numerical simulation of "fuzzy" type in the dissipative approximation of motion of the scale relativity in its non-differentiable hydrodynamic version, it is shown that the separation processes imply both what we call the "relevant dimensions" of the solid components from heterogeneous mixtures and their positions in the fluid–solid mixture velocity field. The above-mentioned phenomena occur in the turbulence regimes of the fluid–solid mixtures. In the scale relativity dispersive approximation of motion, by means of space–time cnoidal oscillations modes of the fluid–mixture velocity field, it is shown that the separation process is controlled through the turbulence regimes of the fluid–solid mixtures. In such a situation three scenarios of transition to turbulence via chaos (quasi-periodicity, sub-harmonic bifurcations, and intermittences) are comparatively given from a theoretical and experimental point of view both for a plasma with complex structures (in the form of double layers), assimilated with fluid–solid mixtures.

1. Introduction

Many theoretical models have investigated the influences of mixture parameters on velocity flows (e.g., the properties of solid particles [1–4]) or the distribution of solid particles due to the rotational regimes of these flows in a fluid [5–7]. A review of the numerical simulations of fluid–solid mixture flows was published by Zhang et al. [8]. The core of present approach can be safely characterized as a smoothed particle method [9], whereby the mixture density is smoothed by a procedure which should be immaterial for the present purpose.

Now, according to the usual concepts [10–12], all of the theoretical models assume that the dynamics of both the fluid and the solid particles in the fluid–solid mixtures occurs on continuous but differentiable curves [10,11,13], so it can be described in terms of continuous and differentiable functions (e.g. density, velocity, temperature fields etc.). These functions are exclusively dependent on the spatial coordinates and time. In reality, a fluid–solid mixture flow proves to be much more complex. Therefore, the above simplifications cannot be expected to explain all of the aspects of the flow dynamics. However, this situation can still be standardized if we consider that the complexity of interaction processes impose different time resolution scales while the evolution pattern leads to different degrees of freedom. From this point of view, we discuss here a complex fluids dynamics [14,15].

In order to develop our theoretical model we assume that fluid–solid mixtures with chaotic behaviour can achieve self-similarity (space–time structures can appear) associated with strong fluctuations at all possible space–time scales [14–16]. Then, for time scales that prove to be large when compared with the inverse of the highest Lyapunov exponent, the deterministic trajectories are replaced by a collection of potential routes. The concept of "definite positions" is replaced by that of an ensemble of positions having a definite probability density [17–23], whose mathematical form will be explained in Section 3. An illustrative

* Corresponding authors.
** Correspondence to: M. Agop, Physics Department, Faculty of Machine Manufacturing and Industrial Management, Gheorghe Asachi Technical University, 59A Prof. dr. docent Dimitrie Mangeron Blvd., 700050, Iasi, Romania.
E-mail addresses: glazar@ub.ro (G. Lazar), m.agop@yahoo.com, pubssci@gmail.com (M. Agop), ochiuzd@yahoo.com (L. Ochiuz).

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example in this respect refers to collision processes in a fluid–solid mixture: between two successive collisions, the particle trajectory is a straight line that becomes non-differentiable at the impact point. Considering that all the collision impact points form an uncontrollable set of points it results that the trajectories become fractals.

Since, in such a context, the non-differentiability appears as a universal property of fluid–solid mixtures, it seems necessary to create a corresponding non-differentiable physics. Indeed, if we assume that the complexity of interactions in the dynamics of fluid–solid mixtures is replaced by non-differentiability, it is no longer necessary to use the whole classical "arsenal" of quantities from standard (i.e. differentiable) physics [10–12].

This topic was systematically developed in [24–26] using the Scale Relativity Theory (SRT) [20,21]. According to SRT the motion along a streamline, followed by a jump from one streamline to another in a Euclidian space, is replaced by motions on continuous but non-differentiable curves (fractal curves) in a fractal space [17–23,27]. Consequently, the Euclidean dynamics of fluid–solid mixture with interactions is substituted by the fractal dynamics of complex fluid free of any constraints. Complex fluid particles move along continuous but non-differentiable curves having a double identity: these curves are both geodesics of a fractal space, and streamlines of the complex fluid. The dynamics of such a complex fluid can be described using fractal quantities (fractal density, fractal momentum, fractal energy, etc.), i.e., functions that depend on spatial coordinates, time and resolution scales. In this respect, the complex fluid has interesting specific properties, such as a hysteretic [28,29].

The present paper gives results extending those from [24,26], taking into account the convection, dissipation and dispersion effects that play an important role in the flow process of fluid–solid mixture. Two distinct approximations of motion of scale relativity in an arbitrary constant fractal dimension are considered: the dissipative approximation which implies the separation process of the solid components from heterogeneous mixtures through the "relevant dimensions" of the solid components and their positions in the fluid–solid mixture, and dispersive approximation which implies control of the separation process of solid components from heterogeneous mixtures through turbulence regimes of the fluid–solid mixtures. In this last case, three scenarios of transition to turbulence via chaos are comparatively described from both a theoretical and experimental point of view, for a plasma with complex structure assimilated with a fluid–solid mixture. Such a flow process frequently occurs in multi-scale type structures, presenting a time diffusion scale, a time convection scale, time heterogeneous reaction, etc., e.g., in fluidized bed material systems [30]. Until now, the problem of the segregation of solid particles from fluid–solid mixtures, which is mainly related to fluidized bed system applications, has only been studied using Eulerian–Lagrangian models (continuum equations to describe the fluid flow [31–33]). In our opinion, the dynamics of multi-scale-type structures can be properly handled only within the mathematical formalism of the SRT. It is thus shown that the presence of convection, dissipation and dispersion induce the specific mechanisms of the mixture separation regimes of solid particles in complex fluid flows.

The present paper is structured as follows: Section 2 — hallmarks of non-differentiability and geodesics equations; Section 3 — dissipative behaviour of the fluid–solid mixture dynamics via non-differentiability, Section 4 — dispersion behaviours of the fluid–solid mixture via non-differentiability; Section 5 — experimental validation of the theoretical model, and Section 6 — conclusions.

2. Hallmarks of non-differentiability. Geodesics equations

Assuming that the curves (fractal, i.e. continuous and non-differentiable) describing the motions of the complex fluid particles are immersed in a 3-dimensional space, and that $\boldsymbol{X}$ of components $X^i(i=\overline{1,3})$ is the position vector of a point on the fractal curve at the time t, the fractal field $F(\boldsymbol{X},t,dt)$, with dt the resolution scale, its total differential expansion up to the third order is [34,35]

$$d_\pm F=\frac{\partial F}{\partial t}dt+\nabla F d_\pm \boldsymbol{X}+\frac{1}{2}\frac{\partial^2 F}{\partial X^i\partial X^j}d_\pm X^i d_\pm X^j+ \\ +\frac{1}{6}\frac{\partial^3 F}{\partial X^i\partial X^j\partial X^k}d_\pm X^i d_\pm X^j d_\pm X^k. \tag{1}$$

The sign " + " corresponds to the forward process, while the sign "−" corresponds to the backward one.

In relations (1) only these terms are finite; any other combinations containing differentials, dt^2, $dX^i dt$, dt^3, $dtdX^i dX^j$, $dt^2 dX^i$ are null taking any asymptotic limit $dt\to 0$(for details see [34,35]).

We note that the first three terms were used only in SRT [20,21] as well as in non-standard SRT (SRT approach with arbitrary constant fractal dimension [36–43]). The forward and backward averages values of (1) take the form:

$$\langle d_\pm F\rangle=\left\langle\frac{\partial F}{\partial t}dt\right\rangle+\langle\nabla F\cdot d_\pm\boldsymbol{X}\rangle+\frac{1}{2}\left\langle\frac{\partial^2 F}{\partial X^i\partial X^j}d_\pm X^i d_\pm X^j\right\rangle \\ +\frac{1}{6}\left\langle\frac{\partial^3 F}{\partial X^i\partial X^j\partial X^k}d_\pm X^i d_\pm X^j d_\pm X^k\right\rangle. \tag{2}$$

Supposing that the mean value of function F and its derivatives coincide, and moreover, that the differentials $d\pm X^i$ and dt are independent, the average of their products coincides with the product of averages, so that Eq. (2) become [34,35]

$$d_\pm F=\frac{\partial F}{\partial t}dt+\nabla F\langle d_\pm\boldsymbol{X}\rangle+\frac{1}{2}\frac{\partial^2 F}{\partial X^i\partial X^j}\left\langle d_\pm X^i d_\pm X^j\right\rangle+ \\ +\frac{1}{6}\frac{\partial^3 F}{\partial X^i\partial X^j\partial X^k}\left\langle d_\pm X^i d_\pm X^j d_\pm X^k\right\rangle, \tag{3}$$

or using the standard relations [20,21]

$$d_\pm X^i=d_\pm x^i+d_\pm\xi^i, \tag{4}$$

where $d_\pm x^i$ is differentiable and resolution scale independent spatial coordinate, and $d_\pm\xi^i$ is non-differentiable (fractal) and resolution scale dependent spatial coordinate,

$$d_\pm F=\frac{\partial F}{\partial t}dt+\nabla F\cdot d_\pm\boldsymbol{X}+\frac{1}{2}\frac{\partial^2 F}{\partial X^i\partial X^j}\left(d_\pm x^i d_\pm x^j+\left\langle d_\pm\xi^i d_\pm\xi^j\right\rangle\right)+ \\ +\frac{1}{6}\frac{\partial^3 F}{\partial X^i\partial X^j\partial X^k}\left(d_\pm x^i d_\pm x^j d_\pm x^k+\left\langle d_\pm\xi^i d_\pm\xi^j d_\pm\xi^k\right\rangle\right). \tag{5}$$

Even if the average value of the fractal coordinate $d_\pm\xi^i$ is null [20,21]

$$\left\langle d_\pm\xi^i\right\rangle=0, \tag{6}$$

the situation can still be different for a higher order of fractal coordinate average. Indeed, let's focus first on the averages $\langle d_\pm\xi^i d_\pm\xi^j\rangle$. If $i\neq j$, these averages are zero due to the independence of $d_\pm\xi^i$ and $d_\pm\xi^j$. So, using the fractal equations [20,21]

$$d_\pm\xi^i=\lambda_\pm^i\left(\frac{dt}{\tau}\right)^{1/D_F}, \tag{7}$$

where $\lambda_\pm^i$ are constant coefficients with statistical meanings (for details see [18–21]), dt/τ is the normalized resolution scale, with