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Physics of Solution of Primary Task of the Turbulence Problem

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Abstract

The paper discusses one outcome of the physical viewpoint to the turbulence problem specifying the primary task of the solution of this problem in the formulation of the turbulence mechanics in the spin-included form with the spin understood as a local average dynamic measure generated by non-local eddy structure of the turbulent flow field. Some upshots of the solution of this task in the form of the postclassical turbulence mechanics are commented.

Keywords: hierarchic stochastic systems, turbulence spin, postclassical turbulence mechanics

1. Introduction

The widely cited characterization of the turbulence problem by R. Feynman (attributed also to A. Einstein, W. Heisenberg, A. Sommerfeld) as "a last remained unresolved problem of classical physics" mandates the solution of this problem in the frame of principles of classical physics, though leaving unspecified which kind of result (or results) can claim to be the solution of the problem. The current paper specifies this mandate stating firstly the position of the turbulence problem in the systemic framework of organization of theories of physical fields (Heinloo, 2012, 2009). The framework (Subsection 2) treats the descriptions of physical fields as the elements of a system of particular theories of divided competence including the classical fluid mechanics, statistical fluid mechanics and the turbulence mechanics (TM). It esteems the Richardson-Kolmogorov turbulence conception (Richardson, 1922; Kolmogorov, 1941) (which explains the organization of the turbulent flow field in incessant restoration of its hierarchic eddy structure realized in the cascading process with the large-scale eddies energetically fed and orientated by the average flow) and enlightens the primary task of the solution of the turbulence problem in formulation of the TM in the form including spin (which is understood as a local average dynamic measure of the turbulent flow field generated by its non-local eddy structure). Section 3 enlightens the prerequisite of the definition of the turbulence spin – inclusion of curvature of velocity fluctuation streamlines passing the flow field points to the characteristics of states of the flow field in the infinitesimal surroundings of the flow-field points. The outcome of solution of the primary task in the form of the postclassical turbulence mechanics (PCTM) (Heinloo, 2004a, 2013a, 2013b) is commented. Section 4 characterizes the situation in the TM called fourth by the formulation of the PCTM as critical in respect to the classical turbulence mechanics (CTM). The critique is represented as a mandate to replace the CTM with the PCTM in the discussion of turbulence-related problems foreseeing the changes in the turbulence problems treatment having a paradigmatic extent.

2. Systemic Context of the Turbulence Problem

The systemic organization of descriptions of physical fields is grounded on a generalization of the systemic nature of any probabilistic description (compiling the descriptions of the members of the family of random events, of the probabilistic structure of this family and of the conditions of formation of this structure) to the description of hierarchic stochastic fields (Heinloo, 2004b). If applied to the physical situation it suggests the organization of the descriptions of different types of physical fields according to Figure 1 (Heinloo, 2009, 2012). In addition to the "node theories" (particularized in Figure 1 for the two lowest information coding levels) the represented in Figure 1 organization comprises also the theories connecting the neighboring node theories (called in (Heinloo, 2009) the "recoding theories").

A significant property of the organization presented in Figure 1 is the correlating similarities of formalisms of the theories included and the similarities of their relative location. So, all theories of the lowest information coding level have independent axiomatic basis, the theories of the second information coding level represent statistical theories connecting the respective pairs of the node theories of the lower information coding level as the descriptions of the random events and of the conditions of formation of statistical properties of random events. The other type of the similarities is related to the theories located symmetrically in respect to the classical (Hamiltonian) mechanics − the common origin of the setup of descriptions of macroscopic and microscopic fields. Besides the similarities between the formulation of the statistical mechanics and the quantum mechanics, of the electrodynamics and the classical fluid mechanics (the similarity increases if instead of the classical fluid mechanics its relativistic version (Heinloo, 2010a) is considered) and of the statistical fluid mechanics and the statistical theory of strong interaction (reflected, in particular, in the commented in (Monin & Jaglom, 1975) possibility of formulation of statistical description of turbulence in the form of the equation similar to the Schwinger equation in quantum theory of fields of strong interaction), the indicated type of similarity expects also a similarity between the formulation of the TM (in the form including spin) and the theory of strong interaction denoted by SI in Figure 1. The presence of the turbulence spin (understood as the local dynamic average measure of eddy rotation) is a direct outcome of the Richardson-Kolmogorov turbulence conception (Richardson, 1922; Kolmogorov, 1941). In addition to predicting the turbulence spin (representing mechanical analog of the spin in physics of fields of strong interaction) this conception declares the need to treat the transmutations, occurring in the turbulent media in the form of incessant restoration of the hierarchic eddy structure of the turbulent flow field with full permanence of the medium itself as an original entity, as a physical form of motion. The similar need is declared in (Frenkel, 1949) being essential also for understanding of fields of strong interaction. Finally, the predicted by the Richardson-Kolmogorov conception scaling structure of turbulent flow field is recognized in (Kuzmin & Patashinskii, 1972) representing a property common to all fields of strong interaction.

Besides setting the turbulence problem into the context of physics as a whole and esteeming the Richardson-Kolmogorov conception in this context, the systemic organization in Figure 1 particularizes the mechanical context of the turbulence problem. It delegates the description of specific properties of turbulence to the TM and the statistical fluid mechanics of the highest determination level interconnected by the respective "recoding theory". The latter specifies the flow field characteristics within the TM as the moments of the probability distributions characterizing the motion states within the statistical fluid mechanics, with the competence of selecting these moments delegated to the TM. The role of the TM as determining the conditions of formation of specific properties of the probability distributions characterizing the motion states within the statistical fluid mechanics ascribes the formulation of the TM with the status of the primary task of any solution of the turbulence problem. The "recoding theories" connecting the TM and the statistical fluid mechanics with the classical fluid mechanics, describing the flow states in infinitesimal space-time regions (specified from the position of the higher determination level as random events), do not remove this status.

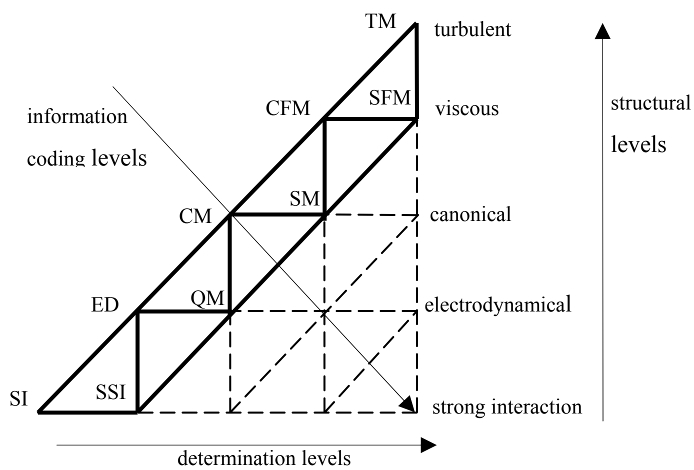

Figure 1. Systemic organization of descriptions of physical fields

The following abbreviations are used: TM – turbulence mechanics; CM – classical mechanics; SM – statistical mechanics; CFM – classical fluid mechanics; SFM – statistical fluid mechanics; ED – electrodynamics; QM – quantum mechanics of fields without spin; SI – theory of strong interaction; SSI – statistical theory of strong interaction.

3. The Solution of the Primary Task

3.1 Turbulence Spin

The basic step to solve the primary task of the turbulence problem in the sense specified above is the definition of the turbulence spin. This task is solved in the setup of postclassical turbulence mechanics (PCTM) (Heinloo, 2004a, 2013a, 2013b). The solution is preceded by an axiomatic step constituting the need to include the curvature of velocity fluctuation streamlines passing the flow field points to the characteristics of the flow field states in the infinitesimal surroundings of the flow-field points (as random events) and is realized through the definition of the turbulence spin, $\boldsymbol{M}$, as

$$\boldsymbol{M} = \left\langle \boldsymbol{v}' \times \boldsymbol{R} \right\rangle, \tag{1}$$

where $\boldsymbol{v}'$ is the velocity fluctuation, $\boldsymbol{R}$ is the curvature radius-vector of the velocity fluctuation streamlines passing the flow field points, expressed through the respective curvature $\boldsymbol{k}$ as $\boldsymbol{R} = |\boldsymbol{k}|^{-2}\boldsymbol{k}$, and angular brackets denote statistical averaging with $\boldsymbol{R}$ included to the arguments of the probability distribution. The defined spin has the sense of average density (per unit mass) of the moment of fluctuating constituent of momentum with $\boldsymbol{R}$ standing for the (random) arm of the moment. Definition (1) is coupled with the definition of the respective to the spin kinematic flow-field characteristics – the gyrocity,

$$\boldsymbol{\Omega} = \left\langle \boldsymbol{v}' \times \boldsymbol{k} \right\rangle, \tag{2}$$

having the sense of average angular velocity of rotation of medium particles at a flow-field point in respect to the random curvature centers of velocity fluctuation streamlines passing this point. Notice, that the representation of $\boldsymbol{v}'$ as the sum

$$\boldsymbol{v}' = \overline{\boldsymbol{v}'} + \boldsymbol{v}'', \tag{3}$$

where the overbar denotes averaging over the situations with fixed $\boldsymbol{R}$ and with $\boldsymbol{v}''$, determined as $\boldsymbol{v}'' = \boldsymbol{v}' - \overline{\boldsymbol{v}'}$, independent from $\boldsymbol{R}$ and $\boldsymbol{k}$, evidences of only a part of the velocity fluctuation (specified as $\overline{\boldsymbol{v}'}$) contributing to the spin and the gyrocity.

3.2 PCTM

Definitions (1) and (2) perform the turbulence decomposition into the orientated and not-orientated constituents with the energy densities per unit mass

$$K^{\Omega} = \tfrac{1}{2}\boldsymbol{M} \cdot \boldsymbol{\Omega} \quad \text{and} \quad K^{0} = K^{\mathrm{t}} - K^{\Omega},$$

respectively, where $K^{\mathrm{t}} = \left\langle v'^2 \right\rangle / 2$ is the density of the total turbulence energy per unit mass, and mandate the inclusion of the equation for spin (with the algorithm for derivation of this equation included into the definition (1)) to the turbulent motions description setup. The PCTM realizes the mandate within common principles of continuum mechanics (Sedov, 1987), particularized in (Dahler; 1959; Dahler & Scriven, 1961; Eringen, 1980; 1966; Lukaszewicz, 1999) for the description of continua with spin.

One corollary of the inclusion of spin into the setup of the TM is the declaration about asymmetry of turbulent stress tensor with the dual vector to the antisymmetric constituent of the stress tensor expressed through the local flow-field characteristics as (Heinloo, 2012; 2013a)

$$\boldsymbol{\sigma} = \rho \left\langle \boldsymbol{v}_{\boldsymbol{R}}'' \times \boldsymbol{v}'' \right\rangle \tag{4}$$

where $\boldsymbol{v}_R''$ denotes the $\boldsymbol{v}''$ projection to the direction of $\boldsymbol{R}$. The defined in (4) $\boldsymbol{\sigma}$ characterizes the effect of the momentum transfer in the direction of $\boldsymbol{R}$ either increasing or decreasing the rotation characterized by the spin. For $\overline{\boldsymbol{v}'}$ neglected this direction remains unspecified, $\boldsymbol{v}_R''$ identifies with $\boldsymbol{v}''$ and $\boldsymbol{\sigma}$ specifies as identically zero. This is just the situation constituted within the CTM.

Definitions (1) and (2) specify the characteristic spatial scale of turbulence ℓ, determined from $\boldsymbol{M} = \ell^2 \boldsymbol{\Omega}$. This situation can be generalized to a hierarchy of spatial scales starting from the representation of the velocity fluctuation as a superposition of its uncorrelated constituents (Heinloo, 2011, 2010b, 2008a)

$$\boldsymbol{v}' = \sum_n \boldsymbol{v}[n]', \tag{5}$$

where $\boldsymbol{v}[n]'$ (in which $n = 1,2,3,...$) denote the velocity fluctuations of different order, formed as an outcome of application of a sequence of averaging procedures instead of just one act of averaging within the conventional approach. Using (5) we have from (1)

$$\boldsymbol{M} = \sum_n \boldsymbol{M}_n, \tag{6}$$

where

$$\boldsymbol{M}_n = \langle \boldsymbol{v}[n]' \times \boldsymbol{R} \rangle, \tag{7}$$

in which $\boldsymbol{v}[n]'$ correlates with the constituents of $\boldsymbol{R}$ qualified as the curvature radii of the $\boldsymbol{v}[n]'$ streamlines. Defining the respective to $\boldsymbol{M}_n$ spatial scales ℓ_n from $\boldsymbol{M}_n = \ell_n{}^2 \boldsymbol{\Omega}_n$, where $\boldsymbol{\Omega}_n$ denotes the respective to $\boldsymbol{M}_n$ gyrocity, the sum in (6) appears to express the decomposition of the spin over the selected scales of motion. The modification of the setup of the PCTM to the spin-decomposed form enables an explicit introduction of properties of scaling of turbulence into the average turbulence description invariant in respect to any particular decomposition. As shown in (Heinloo, 2010b), the step enables to distinguish (and systematize) different types of cascading processes in turbulent media which substantially enriches the competence of the TM in discussing turbulence problems.

4. Discussion

While the systemic viewpoint in Section 2 sets the turbulence problem into the physical context, removes from the classical fluid mechanics the competence of description of turbulence and explains the formulation of the TM in the form including spin as the primary task of solution of the turbulence problem, then the PCTM realizes this task within the formalism following the classical principles of statistical averaging and continuum mechanics with the novelty concentrated in just one only step – the inclusion of the curvature characteristics of the velocity fluctuation streamlines to the characteristics of the flow field states in infinitesimal surroundings of flow field points. Besides returning the turbulence problem to the physical background and demonstrating the efficiency of the classical physics principles in advancing the TM, the formulation of the PCTM also includes several future tasks including the modification of the statistical fluid mechanics replacing the characterization of flow field in infinitesimal surroundings of the flow field points by the flow velocity $\boldsymbol{v}$ with the pairs $(\boldsymbol{v}, \boldsymbol{R})$ and advancing the methods of turbulence measurements so far adjusted for the needs of the CTM. The formulation of the PCTM also increases the number of applications of TM, outlined in several examples reported and/or referred to in (Heinloo, 2013b, 2008b, 2004a; Heinloo & Toompuu, 2013; Heinloo, Toompuu, & Lilover, 2012). The examples can be arranged into three groups. The first group collects the desciptions of stationary flows in round tubes, plain channels and between rotating cylinders, the desciptions of non-stationary flows in round tubes and bottom layers of natural water bodies formed under the influence of periodic pressure gradient, and of magneto-hydrodynamic flows in plain channels under different mutual orientations of the flow-field characteristics and the induction of the magnetic field. The second group comprises models of different geophysical processes. Within this group the models of the effects of eddy-to-mean energy transfer in geophysical jets, of the formation of alongshore flows in natural water bodies, of the turbulence rotational viscosity effects in the dynamics of the Antarctic Circumpolar Current and in formation of zonal winds, of the stratification and gyrocity effects on the wind-driven flows in the upper ocean, and of the meridional distribution of gyrocity in the Pacific Ocean are formulated and discussed. The third group treats the problems of turbulent diffusion. Within this group the problems of reaction of the upper ocean to periodical cooling and heating, of layering of the thermohaline fields due to the double diffusivity, of turbulent transport of salinity in the region of the Gibraltar Salinity Anomaly, and of the turbulent transport of suspended matter in the bottom layers of natural water bodies and river estuaries are discussed. The number of applications of the PCTM may be substantially larger if the PCTM is applied in structurally decomposed form.

In contrast to the PCTM the CTM excludes the spin. The PCTM agrees with the exclusion for the velocity fluctuation constituent $\overline{\boldsymbol{v}'}$ absent in (3). In terms of the turbulence viscosity the exclusion declares the turbulence viscosity properties represented by the turbulent shear viscosity (associated with the symmetric constituent of turbulent stresses) only. The situation neglects the type of turbulence viscosity associated with the antisymmetric constituent of turbulent stresses (called within the PCTM the turbulence rotational viscosity) the effects of which dominate over the effects of the turbulence shear viscosity. The domination follows from the large-scale turbulence constituent responsible for the spin immediately interacting with the average flow. In a most drastic form the inconsistency of the CTM with the actual situation raises in describing the observed situations of eddy-to-mean energy conversion or up-gradient momentum transfer (Starr, 1968), agreeing with the CTM only if negative values of the turbulent shear viscosity coefficient are accepted. This kind of viscosity coefficient values is, however, excluded by the physical essence of viscosity.

The criticism of the PCTM in address of the CTM is not a scholastic debate about some nuances in the TM. Insofar as the TM belongs to the basic disciplines of a number of fields of knowledge from the weather prediction to engineering, any hint to probable shortcomings in the setup of the CTM should be subjected to attentive analysis. The required analysis must begin from the examination of the formalism of the PCTM. Being convinced in the correctness of this formalism the critique of the PCTM in address of the CTM should be estimated as a mandate to replace the CTM in discussion of turbulence-related problems with the PCTM foreseeing wide-ranging changes in the turbulence problem treatment having a paradigmatic extent. This kind of changes are always accompanied with strong conflict of interest in which the side attempting to change the status quo relies on arguments of an expanded scientific and/or conceptual background while the side defending the status quo relies on canonical arguments. The conflict is commonly solved in favor of the more general, trustworthy and productive paradigm.

5. Conclusion

The paper discusses a physical point of view to the turbulence problem specifying the primary task of the solution of this problem in formulation of the TM on the bases of the Richardson-Kolmogorov turbulence conception. The proposed solution of this task results in the form of the PCTM. The peculiarities of the PCTM follow from complementation of characterization of properties of the velocity field in the infinitesimal surroundings of flow field points besides the flow velocity (as it is done within the CTM) also by the curvature of the velocity fluctuation streamlines passing these points. The complementation grounds the characterization of the average turbulent flow field besides the characteristics applied within the CTM on the turbulence spin and the gyrocity, radically changing the state-of-affairs in the TM. As an example, the turbulence viscosity properties become characterized within the PCTM besides the turbulent shear viscosity, as constituted within the CTM, also by an additional viscosity type. The changed situation calls fourth the necessity of critical analysis of the results grounded on the CTM, the complementation of the methods of the turbulence experimental research (so far adjusted for the needs of the CTM) and points out a way to modify the statistical fluid mechanics, so far neglecting the effects of curvature of velocity fluctuation streamlines.

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