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Compendium of Near-Wall Interaction Problem and Boundary Conditions on Smooth Solid Boundaries in Dynamics Problems of Continuous Fluid Media

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Boundary conditions for boundary value problems of macro-thermo-mechanics in conditions of fluid philicity and fluid phobicity effects occurrence, as well as of processes of conductive and radiative energy transfer through contact layers of solid and fluid binary interacting phases are presented.

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I. Introduction

The topic of this study is characterized by high *complexity* and deficit in the degree of validity of our understandings of physical essence of phenomena considered here, as well as theoretical and applied *topicality* of problems discussed in the paper.

The difficulty stems from the fact that the extremely wide class of internal (channels) and external (flow around bodies) problems of macro-thermo-mechanics includes fragmentarily solid borders with inevitable appearance of force and thermal interactions of contact molecular-atomic layers of respective phases. These processes are accompanied by effects of fluid phase adhesion (or anti-adhesion) to wall (from wall) requiring, as it will follow from subsequent stipulations, *additional studying*.

Here it is reasonable to clarify: prefix *"macro-"* in the term of *"macro-thermo-mechanics"* means that in this theory the scales of macro-motions are defined by topology of *physical point*, and micro-, meso-, nano- and molecular-atomic motions (hereinafter, simply, micro-motions) – by characteristic inter-corpuscle distances (liquid) or mean free paths of these monads (gases). The expressed qualitatively corresponds to Knudsen numbers $Kn < 10^{-2}$ for dropping liquids and $Kn < 10^{-3}$ for sufficiently dense gases [1, 2].

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Topicality is associated with at least two principally important circumstances.

- Boundary conditions, including those on walls, shall extrapolate the corresponding to phenomena physics solutions of respective closed model systems of integral-differential equations of dynamics of medium inside $\overline{V}$ area, i.e. in $S \to V$ direction (Fig. 1, notations are discussed below). This aspect is obvious [3], but its effective implementation is fraught with considerable difficulties. As an aside, we note that initial values of field functions can be interpreted as boundary conditions for slice in time $t = 0^+$, i.e. "right" zero, after applying action on boundary surface S of estimated flow area $\overline{V} = V \cup S$, $S = S_{\pm} \cup S_f$ (for $\overline{V}$ case in Fig. 1); hereinafter, the "+" superscript is omitted.

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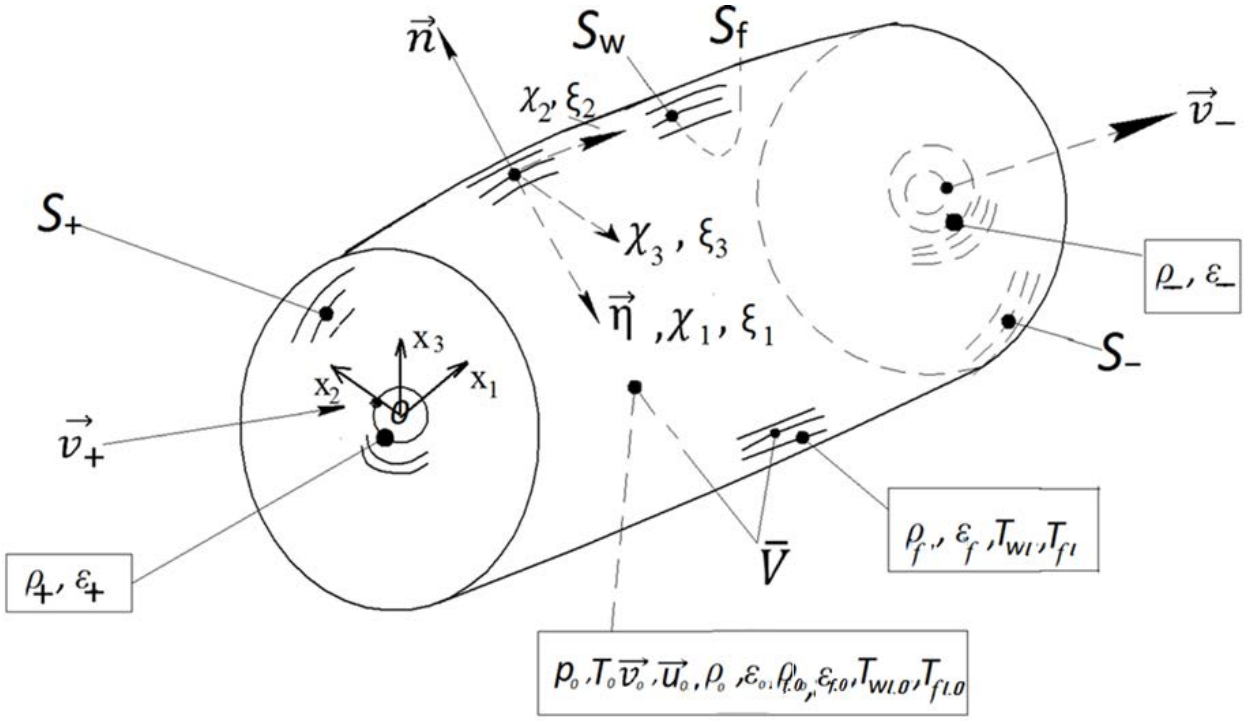

Fig. 1: Example of estimated flow area:
$\vec{v}$ – velocity / momentum per unit mass,
ρ – density, ε – internal energy increment

There are well known correct classical stipulations as well as formulations and rules of setting boundary conditions for quasi-linear differential equations of elliptic, parabolic and hyperbolic types providing (possibly in presence of some additional but not too strict limitations) existence and uniqueness of their solutions. Unfortunately, the considered in the theory being developed mathematical model is strongly nonlinear and, particularly, media $3D_t$ dynamics equations *associate* in themselves, both individually and in aggregate, the specific properties of solutions intrinsic to noted "reference" types of differential equations in partial derivatives of mathematical physics.

- In the most frequently observed intermittent and developed turbulent flows quasi-chaotic pulsations $\vec{v}, \rho, \varepsilon$ of monad/essential substances are distributed by the system of appearing therewith wave disturbances (the media are compressible) with local sound speed throughout the $\vec{x} \in \overline{V}$ space causing thereby aberration of initially fixed boundary conditions [4].

Hence, stipulations of respective boundary value problems turn out to be *objectively incorrect*, since it is obvious that, in general case, the requirement of obtaining *a unique* solution cannot be strictly satisfied. In the situation outlined, in any way, two alternatives are admissible assuming it quite acceptable to understand as *a generalized solution*:

- $\vec{v}, \rho, \varepsilon$ substances values (with rationally normalized dispersion) obtained according to *algorithm* described in *work* [4], with possible involvement of procedures of their *self-setting* in outflow section S_- (see Fig. 1) at completing computation time slots;
- Averaged, over *ensemble* of realizations of the respective boundary value problem in the range of low-level macro-scales wave and frequency numbers, values of noted variables at the forecast that these average values exist and admit their acceptably stable determination.

II. Main Part

We proceed with exposition of *the first topic* of the work (see the title), noting that notations not specified in the text are explained in publication [1].

The problem of identifying and explaining the laws of near-wall interaction of solid boundary with fluid phase actually determining respective boundary conditions and properties of flow at distances of strong, medium and weak action of surface molecular-atomic layer of the wall has been and remains the subject of scientific discussions. Intensity of these discussions in different historical periods had intermittent nature, but, as we observe, it has been significantly increasing in recent years largely due to development of nanotechnologies.

One of the main points in discussions there was a dilemma of existence or absence in the dynamics of the effect of sticking (slipping) fluid phase to (on) solid wall, or some combination of these two possibilities. Since a fairly complete overview in time aspect of essence of the mentioned studies based on theoretical prerequisites and experimental data is contained in compilatory part of monograph [2] chapter 7, we only confine to fixation of main results of these studies and statement of status of the specified problem in current years. The expressed below summary will, of course, take into account limitations in *Kn* numbers indicated in the introduction.

It is important to note that this problem has attracted attention of prominent physicists and, in particular, fluid mechanicians since 18th century up to the present day. It is understood that instrumental/technological equipment of those distant years allowed carrying out experiments only in the framework of macro-resolution, for example, experiments with water and mercury in glass tubes with minimum diameters of 1 mm [5 – 7].

Omitting details of judgments, we present general and quite reasonably formulated in monograph [2] results of analytical and experimental studies on the topic under discussion.

- By the middle of 20th century there established *"an opinion that slipping is possible, but it cannot be measured reliably by any available experimental techniques. Hence, for all practical applications the slipping is of no importance …"*, and in the literature almost exclusively *"for viscous liquid only the condition of sticking was used"*. The noted, of course, is referred also to sufficiently dense gases.
- For the current moment, *"despite numerous studies (experimental precision, up to molecular-atomic layers, as well as analytical at deterministic and statistical levels of molecular dynamic simulations – our addition) the final mechanism of slipping remains unclarified"* due to the following basic (in our opinion) reasons (see [2], 410, 430, 431):

* *"Slipping acts on molecular level"*
* *"Apparently, the thinnest layer of molecules of liquid yet still firmly "sticks" to solid body, but velocity gradient is so great that molecules above this layer move. The thickness of such "stuck" layer can be equal to only one layer of molecules ... or some higher";*
* *According to modern understandings … flows of liquid have an inner layer of air (or other gas), and that leads to greater effective slip lengths"* as in effect of *"lotus leaf".*

Note: in this paragraph, the text marked with quotes and additionally highlighted in italics is the citation from publication [2].

In terms of discussions and on phenomenological level of understandings we suggest and try, if possible, to justify, at least qualitatively, the author's view on the nature of near-wall interaction between surface layers of solid and fluid phases, which, in assumed absence of solid phase surface nano-structurization and gas interlayer between contacting pair of wall/dropping liquid, in principle, consistent with the last three statements marked with "asterisks".

Anticipating the stated below, we note that in Fig. 1 being the sample of estimated flow area for internal problem of fluid/gas dynamics, in addition to the previously mentioned, the following notations are specified: $S_w \wedge S_f$ – contacting solid and fluid surfaces; $\vec{\eta} \wedge \vec{n}$, x_κ and $((\chi = \chi_1,\chi_2,\chi_3) \vee \chi_k) \wedge ((\xi = \xi_1,\xi_2,\xi_3) \vee \xi_k), k = 1,2,3$ internal and external normals to S, global (for entire estimated flow area $\overline{V}$), as well as local Cartesian coordinate systems for micro-, meso-, nano- and molecular *linear* scales for substance-field (to the left of $\wedge$ sign; hereinafter, to shorten the records, simply, *micro-scales*), and macro-scales of physical points (to the right of $\wedge$ sign), respectively. Next: $p \wedge T$ is compression pressure and absolute temperature; subscripts $+$, -, *w*, *f*, *wl*, *f l*, 0 is assignment of field functions to S_+, S_-, S_w, S_f surfaces and initial values of these functions. It is also understandable satisfaction of collinearity conditions $(i_k \chi_k \wedge i_k \xi_k) \| (\vec{\eta} \wedge \vec{n})$, where i_k is unit vector of respective coordinate axis. Finally, equalities $\chi_1 = \chi \wedge \xi_1 = \xi$ for coordinate axis, orthogonal axis $S_w \wedge S_f$, are introduced for further simplification of notations in graphic representations related to this coordinate direction.

We now turn directly to the problem of binary interaction of $S_w \cup S_f$ boundaries, but first note the following. An understanding seeming, at first sight, elementary, but as a whole, obviously fair, of qualitative type of force interaction between two individually allocated *molecules* of the substance has been widely established. Namely, the emergence and rapid growth of *repulsive*/repulsion force during *approaching* of these molecules/corpuscles at distances less than the distance corresponding to quasi-equilibrium thermal power state, and vice versa: *attractive* forces during these molecules motion in the directions of their *moving apart* from each other with achievement of optimum attractive binary action (see χ* point below in Fig. 2) and further asymptotic approaching of this force to zero with this divergence increasing. Here, as in the following, the *quasi* prefix in the "equilibrium thermal power state" term has quite a distinct sense consisting in understanding that, in this position, the said micro-scale substance-field oscillates in conditions of kinetic/dynamic impacts from the micro world containing it.

It is appeared consistent to take as a working hypothesis the assumption of a certain similarity of events specified in preceding paragraph with attractive/repulsive influence of surface molecular-atomic structure of the wall on fluid phase in accordance with illustrative scheme in Fig. 2. The accepted hypothesis assumes existence of some similarity with noted case of single-phase structure of aggregate power action of electron shells and atomic nuclei in molecules of the binary phases being considered. In Fig. 2, by shaded background in 3D image the estimated change of $\vec{F}_a$ force of discussed here surface interaction of molecular-atomic layers $S_w \cup S_f$ in $\chi = \chi_1$ direction of χ_κ coordinate system is shown with highlighting by blackened reference points ● quasi-equilibrium position on surface S_f of molecules with $(\chi_1 = \chi^0, \chi_2, \chi_3) \in S_f$ coordinates; therewith macro-motion velocity $\vec{v} = 0$ for $\xi >> \chi^0$, i.e. with static macro-state of continuous fluid phase at considerable distances from S_w.

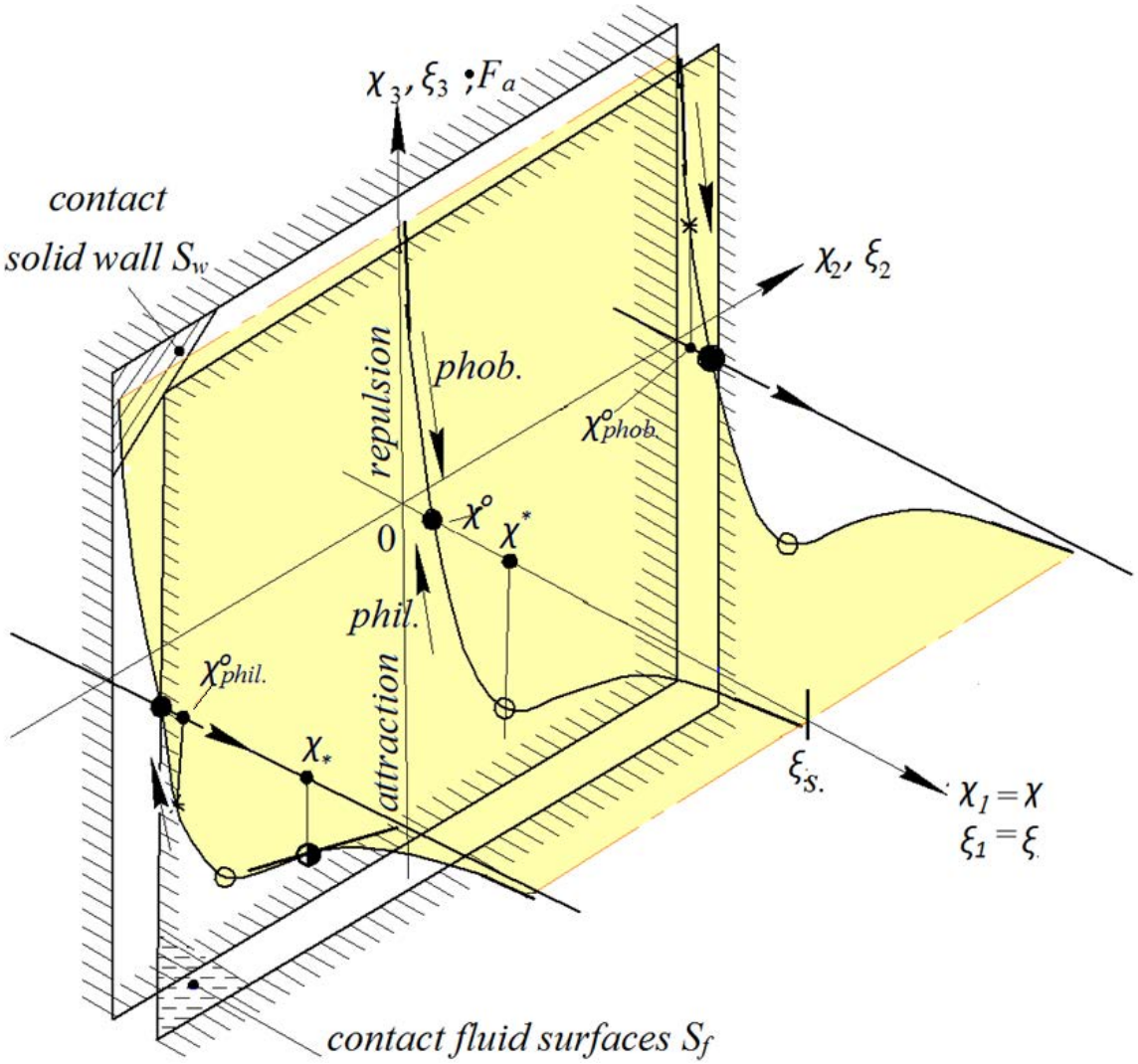

Fig. 2: Conditional scheme of force interaction of contact surfaces of smooth solid S_w and fluid S_f phases in micro-scale representation at static macro-state $\vec{v}\Big|_{\xi>\xi_{s,}} = 0$

Self-setting of the noted state, from initial position of fluid contact layers $\chi^0_{phil} \vee \chi^0_{phob}$ to χ^0 is characterized eventually by absence of deformation velocities $\vec{v}_d$ and physical points $\ni (\vec{v} = \vec{v}_c + \vec{v}_d = 0)$ centers of mass $\vec{v}_c$ motion. Author's understanding of decomposition of motion of medium elementary particles is presented in paper [9]. This movement is effected, as noted, by motion of *corpuscles* of these extremely small macro-formations from their (corpuscles') initial in χ coordinate χ^0_{phil} positions for fluid-philic and χ^0_{phob} for fluid-phobic surfaces $S_w \cup S_f$ to position of force quasi-equilibrium χ^0. The specified

transitions are shown in Fig. 2 conditionally by multi-directional pseudo-vertical arrows. Hereinafter, under the term $\vec{v}_d$ deformation velocity we mean cumulative velocity of both distortion of volume and shape of physical point and rotation about its center of mass.

More detailed, therewith still purely qualitative, schemes of processes of micro-scale self-setting are shown in Fig. 3; however, not only for conditions for achieving *static* quasi-equilibrium power macro-state of contact layers of solid and fluid media (Fig. 3a,b), but also for general case of *dynamic* near-wall motion (Fig. 3c). In Fig. 3a and 3b the vertical arrows indicate cumulative binary action of $\vec{F}_a$ force electromagnetic fields transferring molecules with conditional mark * of contact layer S_f from initial (at the moment of fluid touching the wall S_w) non-equilibrium state to position with mark ● of achieving power quasi-equilibrium for the cases of occurrence of adhesion (philic) and anti-adhesion (phobic) effects, respectively., The overall directivity of solid phase surface external electromagnetic field impact on fluid phase corpuscles is emphasized here symbolically by sharp corners of blackened triangles.

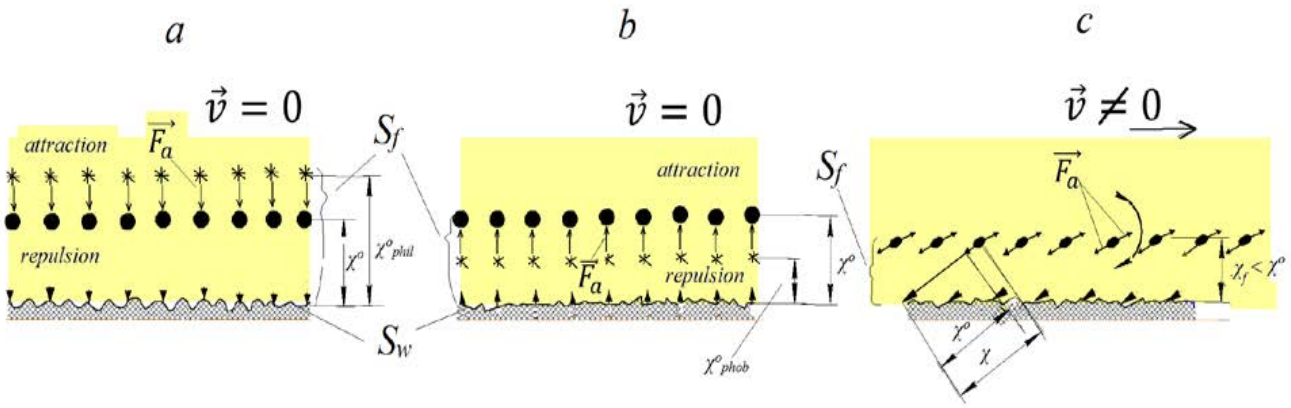

Fig. 3: Schemes of deformation of electromagnetic fields and corpuscular layer, contact surface S_f with respect to solid smooth-wall surface S_w in micro-scale representation in static $\vec{v}\big|_{\xi>\xi_s.}=0$ (a, b) and dynamic $\vec{v}\big|_{\xi>\xi_s.}\neq 0$ (c) macro-states

Fig. 3c shows purely figuratively time slice of dynamic near-wall interaction accompanied, in our opinion, by distortion positively correlating with orientation and level of external flow velocity $\vec{v}$, *directivity* of initially orthogonal to S_w (in smooth wall case) force electromagnetic fields. These fields are created jointly by surface molecular-atomic structures $S_w \cup S_f$ and lead, as a consequence, to deformation shifts of associated in understandings of "substance-field" corpuscular groups of fluid phase. The indicated force field deformation is marked symbolically in Fig. 3c with an arc oriented clockwise for the case of fluid phase motion above contact layer from left to right. The described situation contains a prerequisite of a possibility of some accommodation aberration in the properties of surface molecular-atomic structures *cohesion* in level and direction of its (cohesion) action as S_w wall and, especially, S_f surface, accompanied by self-setting of dynamically balanced near-wall flow, but with fixed centers of mass $(\vec{v}_c=0)$ of macro-particles belonging directly to S_f surface. It is understood that the prerequisite expressed demands its subsequent verification.

So, if we assume that the suggested phenomenological concept of near-wall interaction as portion of a pluralistic set of alternate approaches possess a predominant validity, it is possible, as main conclusions from the first topic of this article important for further discussion, to state the following.

a) At complete pouring of fluid-philic fluid phase onto the wall its contact layers, figuratively saying, somewhat *flatten*/shift to S_w without changing the volume (at fixed pressure) reducing to some extent depending on specific properties of medium the distance of corpuscles from solid phase surface $\chi^0 < \chi^0_{phil}$. We fix the noted as *event of approaching* (see Fig. 3a).
b) In a similar action with fluid-phobic phase we have $\chi^0 > \chi^0_{phob}$ and observe the *event of* substances *moving apart* from S_w, and molecular movement opposite to the previous type is realized (see Fig. 3b).
c) In dynamics (see Fig. 3c), the contact layer S_f, regardless of philia or phobia category in relation to S_w layer, is adjacent to this surface and in such a way that velocity component of the physical points

with $\xi \in S_f$ coordinate center of mass $\vec{v}_c$ is equal to zero. Hence,

$$\bar{v} = \vec{v}_d\left(0, \xi_2, \xi_3; t\right), \qquad (1)$$

where $\vec{v}_d$ is deformation velocity of marked physical points different from zero *only* for non-stationary modes of fluid medium motions.

We now turn to the *second topic* of the study mentioned in the title of this work. Therewith, due to the obvious complexity of the discussed phenomena and to reduce the article scope we confine ourselves henceforth to consideration of the boundary conditions only for the class of *internal* problems of fluid/gas dynamics and only in portions of fluid boundary *S* of estimated area $\bar{V}$ adjacent to its solid fragments $(S_f \cup S_w) = S \setminus (S_+ \cup S_-)$. Omitted and some other questions (see [8], §§4.10, 4.11) are scheduled to be discussed in subsequent publications.

We refer primarily to the problem of setting *kinematic boundary conditions* on S_f surface with natural use of results of the previous analysis. We introduce indexes used subsequently: $\chi_{Kn} = \xi_{s.}, \xi_{Kn}$ and ζ are *parameters*, for which we will take the next, essentially qualitative and at the *current* time established, unfortunately, by orders, estimates:

$$\chi_{kn} = Kn_{\chi}^{-1}\chi_f, \quad \xi_{kn} = Kn_{\xi}^{-1}\xi_{s.}, \qquad \chi_* = \zeta\chi_{kn}. \quad 0 < \zeta < 1 \qquad (2)$$

Here χ_{kn} is *parameter* of *linear boundary scale* between the largest micro- ($\chi_{\sup}$) and the smallest macro ($\xi_{\inf}$) thicknesses of near-wall interaction fluid layers, which explains the *dualism* of its further notation. We emphasize the general principal stipulation: all newly introduced *linear* dimensional indexes refer to *volumetric* ones, i.e. to 3D macro-scales of physical point *"flattened"* towards ξ_1 axis to levels specified in (2), but without changing its volume, i.e. with preserving the number of corpuscles in this "point". In mechanistic interpretation the $\xi_{s.}$ parameter is at extremely small volume scales of continuity hypothesis validity some average (currently, virtual) *distance* of fluid phase molecular-atomic layers from S_w including $[0, \xi_{s.}]$ range of *close*- and *meso*-action on them of force field $\vec{F}_a$ (see ξ_1 axis in Fig. 2). In relations (2):

χ_f is the *distance* (again, in the just indicated sense) of contact layer S_f corpuscles from S_w (see Fig. 3c), for gases is equal in average to the mean free path of molecules in boundary layer;

$Kn_{\chi} \wedge Kn_{\xi}$ are majorant and minorant values of macro-scale Knudsen numbers as a result of their consensual choice according to estimates given earlier;

ξ_{kn} *parameter* is the distance from S_w, including, in addition to range of *close*- and *meso*-action $[0, \chi^*] \wedge [\chi^*, \xi_{s,}]$ of field $\vec{F}_a$ also $[\xi_{s,}, \xi_{kn}]$ range of *distant*-action of the said force, i.e. a kind of majorant of internal "inertial"/conservative portion of viscous sublayer relatively passively reacting to disturbing impacts from external, in relation to it, flow. We recall that χ^* is the point in vicinity of maximum occurrence of attractive forces (see ξ_1 axis in Fig. 2). Next, χ_* is the point in vicinity of extreme decrease of attractive action of $\vec{F}_a$ with determination of its position on ξ_1 axis by introduction of ζ *parameter* which is now presented as "parameter of uncertainty" requiring its verification in further investigations.

Complexity of the introduced parameters setting is understandable stemming, in particular, from physically conditioned smallness of numerical values $\chi_{kn} \wedge \xi_{kn}$ and their unconditional dependence on various and substantially determining factors: physical and chemical structure of binary pairs being considered, technique and quality of S_w surface treatment, external conditions of near-wall interaction $S_w \cup S_f$.

Setting valid numerical values or at least possibly narrow ranges of the said parameters changing will obviously require application of precision instrumentation, experimental and theoretical methods of molecular physics researches of current and future time. By analogy with nano-physical understandings of near-wall phenomena (see [2], § 7.2) we call $\chi_{kn} = [0, \xi_{s.}]$ interval the *Knudsen (boundary) layer*, but in 3D macro-scales.

Next, we will observe objectively established practically obvious and therefore undoubtful fact of the most strong interaction of the considered phases in close proximity to the wall, namely, in macro-scales of *viscous sublayer* which, in view of the preceding, predeterminedly includes $\chi_{kn} \wedge \xi_{kn}$ scales in its *interior* portion. Therewith, almost in all scientific studies of the last decades on *continuous* fluids dynamics as a boundary condition on S_w wall the condition of fluid phase sticking to it with setting velocity $\vec{v}(\xi \in S_f) = 0$, including for the most common $3D_t$ stipulations (see compendium of the work *first topic*) is taken. The said condition a priori implies/postulates complete absence in the *dynamics* of any deformation of "stuck" to S_w contact layer S_f. It is clear that this aspect is in contradiction with the concept being developed and, most likely, with the physics of this phenomenon.

The next point: the derived for a *given* pressure gradient strictly linear profile of velocity for steady laminar Couette flow and also believed usually linear or close to that the form of this diagram for turbulent flows

in entire viscous sublayer also including, naturally, Knudsen layer, lead to *complete* or *almost complete* absence of stress tensor divergence in momentum balance differential equation, i.e. $\vec{\nabla}\cdot\mathbf{P}\big|_{\xi\in[0,\xi_{kn}]}=0\vee\approx 0$. At the same time, it is the said component that shall reflect the most severe occurrence of viscosity effects.

Based on the above for *internal* portion of viscous sublayer, i.e. for $(\xi=\xi_1)\in[0,\xi_{kn}]$, we suggest the following *kinematic boundary conditions* with a type of smooth wall (substantial simplification) surface S_w (see also formulas (5.6) in work [9])

$$\left\langle v_{c.k}=\partial v_{c.k}/\partial\xi=0\right\rangle\Big|_{\xi=0+},\ k=\overline{1,3}; \tag{3}$$

$$\left\langle v_{d,k}=du_k/dt,\ u_k=u_{k.0}+\int_0^t\Big(\int_0^{\leftarrow t}a_{d\,l.k}d\tau\Big)d\tau,\ \ v_{d.k}(t>t_+=0\right\rangle\Big|_{\xi=0+}, \tag{4}$$

where $\xi=0+\in S_f$ is right zero (for a given coordinate on S_w the $\xi=0-$ notation, left zero, is used); t_+ is the time of reaching steady-state flow mode. We note that a type of boundary conditions (3) is acceptable with orthogonal to wall and non-zero gradient of particles center of mass velocity $v_{c.k}$, for example, taking into account S_w roughness. This aspect is expected to be considered in subsequent studies.

The next boundary equation of near-wall laws formalism is *dynamic condition* of change of momentum on S_f (see also formulas (2), (4) in work [1])

$$\left\langle\rho\vec{a}_d=\rho\vec{F}-\vec{\nabla}_{\vec{\mathbf{x}}}p+2\vec{\nabla}_{\vec{\mathbf{x}}}\cdot(\overset{\iota}{G}\overset{\iota}{\mathbf{S}}_d)\right\rangle\Big|_{\xi=0+},\ \iota=\varnothing,\bullet,\bullet\bullet;\ \ \vec{a}_d=\vec{a}_{d.l}+(\vec{v}_d\cdot\vec{\nabla}_{\vec{x}})\vec{v}_d \tag{5a}$$

with regard only to deformations of volume and shape of the medium particles.

Here: $\vec{a}_d\wedge\vec{a}_{d.l}$ are full and local accelerations of deformation and rotation of physical point on S_f relative to fixed center of mass of this elementary substrate; pressure p includes proper initial condition p_0 and, as a dependence on functional arguments $\rho\wedge\varepsilon$ [10], the boundary conditions expressed via $\varepsilon_{f.0},\rho_{f.0}$ (see Fig. 1 and the following text); $\overset{\iota}{\mathbf{S}}_d$ and $\vec{\nabla}_{\vec{\mathbf{x}}}$ are deviators of respective tensors according to the specified values of circumflex accent ι and Hamiltonian operator recorded for changes in physical point volume form in *E-system* coordinates [9], finally $\vec{\nabla}_{\vec{x}}$ is Hamilton operator in *L reference system*.

We emphasize an important provision: based on results of researches presented in [9], we have $\dot{S}_d\{v_k\}=\dot{S}_d\{v_{d.k}\}$, i.e., in the matrix of this tensor there are components of velocity $\vec{v}_c$, and on S_f with $S_d\{0\}\big|_{\xi=0+,t>t_+}=0$ the divergence of this tensor is different from zero $\vec{\nabla}\cdot\dot{S}_d\big|_{\xi=0+,t>t_+}\neq 0$.

Keeping on the right of the equation (5a) only the most important, according to our interpretation of near-wall phenomena, components $\iota=\varnothing$ we can write

$$\left\langle\rho\frac{d\vec{v}_d}{dt}=-\vec{\nabla}_{\vec{\mathbf{x}}}p+2\vec{\nabla}_{\vec{\mathbf{x}}}\cdot(G\mathbf{S}_d)\right\rangle\Big|_{\xi=0+}, \tag{5b}$$

where $\mathbf{S}_d$ is deformation tensor deviator.
In steady-state mode, we get the equality

$$\left\langle\vec{\nabla}_{\vec{\mathbf{x}}}p=2\vec{\nabla}_{\vec{\mathbf{x}}}\cdot(G\mathbf{S}_d)\right\rangle\Big|_{\xi=0+,t>t_+}. \tag{5c}$$

We pay also attention to the fact that the existence of $\vec{v}_d$ velocity on S_f in non-stationary processes can be observed in precision physical experiments with resolution close to molecular level and accepted as a fact of S_f surface "slipping" relative to S_w.

For density occurring in boundary relations (5), we have boundary conditions in form (see (6) and the equation (1a) in work [1])

$$\left\langle\ln\rho/\rho_0=-\vec{\nabla}_{\vec{\mathbf{x}}}\cdot(\vec{u}_0+\delta\vec{u})\right\rangle\Big|_{\xi=0+}, \tag{6}$$

where $\rho_0\wedge\vec{u}_0$ are initial values.

Based on the set forth above mechanistic part of the concept and its mathematical formalization with expressions (1) – (6) for internal part of viscous sublayer it is justifiable to expect the change in deformation shift modulus G in equations (5) and critical stress $\overline{P}_{w.cr}=P_{w.cr}/P_{cr}$ of turbulent mono-furcation occurrence on pre- and supercritical fluid media motion modes: $\mathrm{Re}\geq\mathrm{Re}_{cr}$ [1, 11], according to physically quite predictable but, in particular form, conjectural dependences shown in Fig. 4 a,b.

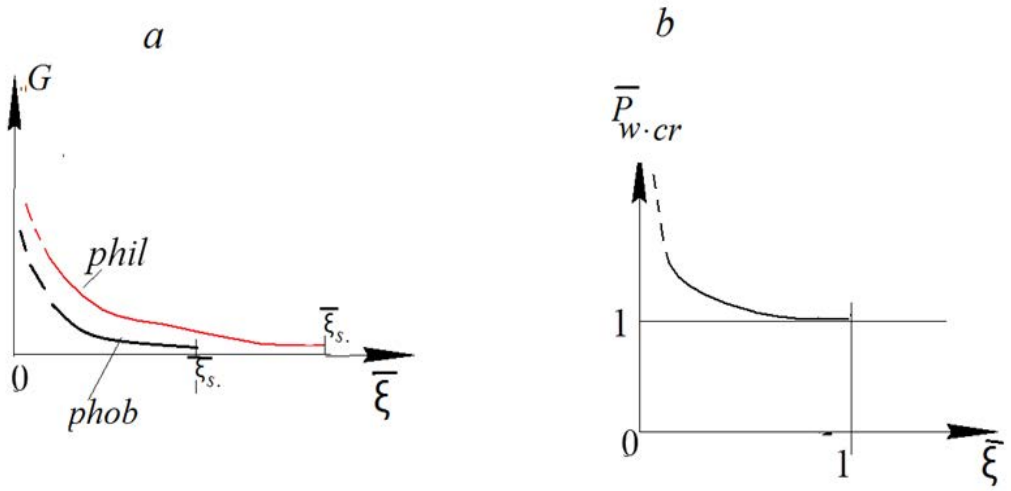

Fig. 4: Conjectured type of shear modulus change *G* (a) and critical stress $\bar{P}_{w\cdot cr}$ for turbulent mono-furcation (b) as functions of distance from wall for scales $\bar{\xi} = \xi / \xi_{kn}$

Here, dashed supplements to curves in their left side, i.e. with $\bar{\xi} \to 0+$, emphasize growing deficit and, in essence, absence of qualitative and, moreover, quantitative verification of these principally important parameters at $\bar{\xi} < 1$.

No less significant are the aspects of description of near-boundary processes of forward $S_w \to S_f$ and reverse $S_w \leftarrow S_f$ conductive and radiant energy exchange, in the case being considered, primarily, heat transfer. To this problem, presented in detail in the first topic of the article, a considerable number of studies (see e.g. monographs [2, 12] and bibliographies there) are devoted. We suggest a model of formalization of the agreed subject of analysis quite consistent in principal to common understandings of physical and mathematical foundations of dynamics of boundary heat flows emerging as a result of energy co-penetrations of contact frequency/wave electromagnetic, including the radiant ones, fields of solid and fluid phases.

In extended stipulation, modeling of these phenomena requires involvement of fundamental equation of internal energy balance increment ε (see e.g. [1], equations (3), (10)) in contact layers of *each* of $S_w \cup S_f$ phases. Then, the boundary conditions for ε on S_w and S_f surfaces take the form of the *two* equations

$$\left\langle \rho \frac{d\varepsilon}{dt} - \mathbf{P} \cdot\cdot \dot{\mathbf{S}} = \rho(q_{cd} + q_r) \right\rangle \Big|_{(\xi=0-)\vee(\xi=0+)}, (\xi = 0-) \in S_w, (\xi = 0+) \in S_f \tag{7}$$

If conductive q_{cd} and radiative q_r forms of specific (per unit of time and mass) energy come from solid phase to fluid phase, then (see also [1], equation (13); [12], §§ 1.5, 8.1, 12.1)

$$\rho q_{cd} = \mathrm{Im}_{fl}(T_{wl} - T_{fl}), T_{wl} > T_{fl} \tag{8a}$$

$$\left\langle \rho q_r = \vec{\nabla}_{\vec{\mathbf{x}}} \cdot \left[\vartheta \int_{2\pi\nu_{\inf}}^{\upsilon_{\sup}} \int (1 - \omega_\nu) I_\nu(\xi, t; \vec{\mathbf{\Omega}}, \nu)\, \vec{\mathbf{\Omega}}\, d\nu\, d\Theta \right] \right\rangle \Big|_{\xi=0+} \tag{8b}$$

Omitting the intermediate manipulations for monochromatic intensity of radiation I_{ν}, in (8b) we have the following integral-differential equation of transfer on binary electromagnetic interaction interval $[0+, \xi] \subset [0+, \xi_{s.}]$

$$I_\nu = I_{\nu.0}(0+, \xi_2, \xi_3, t)\varepsilon + \varepsilon \int_{0+}^{\xi} (\beta_\nu S_\nu - (c^{-1} \partial I_\nu / \partial t))\varepsilon^{-1} d\xi, \quad \varepsilon = \exp\left(- \int_{0+}^{\xi} \beta_\nu d\xi \right) \tag{8c}$$

with boundary condition in form of first summand on the right which, in particular case of *"black"* solid phase (bb – black body) with satisfying Kirchhoff's law, is equal to

$$I_\nu\Big|_{\xi=0+}=I_{\nu.0}=I_{\nu.bb}(T_{bb}),\quad T_{bb}\Big|_{\xi=0-}=T_{bb}\Big|_{\xi=0+}=T_{wl}(0-,\xi_2,\xi_3,t) \tag{8d}$$

and radiation from S_w falls on S_f without distortion.
In expressions (8):

T_{wl} and T_{fl} are absolute current temperatures S_w and S_f depending on functional arguments $\rho \wedge \varepsilon$ (see [10]); $\mathrm{Im}_{f\,l}$ is impedance/thermal boundary resistance of fluid phase $\left(\frac{\mathrm{W}}{\mathrm{M}^3\ {}^o\mathrm{K}}\right)$; for solid phase, this physical parameter is assigned Im_{wl} notation; $I_{\nu.bb}$ is spectral intensity of absolute blackbody radiation into fluidic/flowing medium as defined by Planck formula

$$I_{\nu.bb}=2\hbar\nu^3/\left\langle c_{f\,l}^2\left[\exp(\hbar\nu/kT_{bb})-1\right]\right\rangle,\quad c_{fl}=c_0/\left|\gamma_{f\,l}\right|, \tag{9}$$

where c_0 is the speed of light in vacuum establishing a well-defined order of $d\xi$ and dt differentials ratio in (8c); $\gamma_{f\,l}$ is beam refractive index in a specific fluid medium (in general case, a complex value); $\hbar \wedge k$ are Planck's and Boltzmann's constants; β_ν is spectral attenuation coefficient [m^{-1}]; S_ν is spectral function of the radiation "source" equal to

$$S_\nu(\xi,t)=(1-\omega_\nu)I_{\nu.bb}+(2\pi)^{-1}\omega_\nu\int_{2\pi}In_{f\,l}(\vec{\Theta}\to\vec{\Theta})I_\nu d\Theta, \tag{10}$$

$In_{f\,l}$ is Hopf's *scattering indicatrix* - normalized probability function of directions of incident radiation with unit vector $\vec{\Theta}$ and its dispersion with unit vector $\vec{\Theta}$.

It is easy, by changing or interchanging *wl* and *fl* subscripts, to rewrite the relations (8) – (10) for other options of energy exchange, for example, when q_{cd} and q_r powers are coming in direction from S_f to S_w. For example: $\rho q_{cd}=\mathrm{Im}_{wl}(T_{wl}-T_{f\,l}),T_{wl}<T_{f\,l}$.

To summarize: initial boundary conditions on the wall are written in form of expressions

- (3) – (5) for functions $\vec{v}_c,\vec{u},\vec{v}_d$;
- (6) for density ρ;
- (7) – (10) for internal energy ε.

These conditions can only be established in the process of iterative solution of $3D_t$ problem and, of course, for verified physical modules, parameters and coefficients included in the specified relations. If the put forward phenomenological constructs basically correspond to reality, then such factors to be determined include $\xi_{s.},\xi_{kn},\zeta,G,P_{w.cr},\vartheta,\mathrm{Im}_{wl},\mathrm{Im}_{f\,l},In_{fl}$ and some other indexes noted in work [1].

III. Conclusion

A number of other also substantive stipulation issues of fluid media $3D_t$ dynamics go out beyond the scope of this article, including influence of wall roughness, effects of over- and subsystem disturbing impacts in fluid portions of boundaries, etc., which are scheduled to be considered in subsequent publications.

The incontestable fact that in the future there will be required an in-depth analysis of necessary and sufficient completeness of exposed boundary conditions to obtain solutions in the senses indicated in the introduction.

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