Российская Академия Наук

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PHYSICS OF NON-IDEAL PLASMAS
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Hydrodynamics and transport in Nonideal Plasma

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Nonsolved problems

- **Does nonideal plasma can be described by hydrodynamic equation?**
- **If no, there is no sense to calculate transport properties.**
- **In experiments and simulatons the number of particles very often limited, what are hydrodynamic equations for such a systems?**
- **In some cases subsystems are in nonequilibrium states (no maxwellian disrtribution for heavy partocles, etc.), what are the results for thermodynamics and transport propetries for these systems**
- **What it the reason for plasma crystal creating? Could the attraction be the result of inequilibrium system?**

Non Hydrodynamic plasma effects

- Strong interactions, long range correlations
- Plasma Rheology EOS, Size effects
- Limited number of particles in systems : noThermodynamic limit- nonclassical Hydrodynamics in Dusty plasma, QGP
- System with limited number of particles simulate nanosystems which is very important to applications
- Nonequilibrium thermal energy distribution in Dusty Plasma could create attraction between same sign of quasiparticles

Hydrodynamics and Transport

- Any basic or applied nonideal plasma problem in solution as a rule is based on hydrodynamic equations and constitutional equations are used for relations between thermodynamic fluxes and forces.
- There is the question, are the hydrodynamic equations in the strongly coupled Coulomb systems (SCCS) can be applied and constitutional equations valid for SCCS ?
- It is shown that long range pressure forces even in incompressible fluid exist due to infinity of sound speed and it is the reason for high Re turbulent flows.

Long correlations radius in a plasma

- **In conventional hydrodynamics there are 3 cases – rarefied gas, dense fluid and turbulent regime. In 2 limiting cases rarefied gas and turbulence the correlation radius not small compared to system size and as a result the fluxes become different from linear relations to forces and fluid become rheological.**
- **Correlation radius in SCCS in ideal plasma close to Debye radius, but in nonideal plasma exceeds it due to other correlations, in transition to plasma crystallization the correlation radius increases to the whole volume of the system or infinity.**
- **As a result the hydrodynamic behavior of SCCS become different from linear relations between thermodynamic fluxes and forces.**
- **Another result is that in the transition regime from gas to crystal system goes from pure dissipative to elastic media and SCCS become Non Newtonian with Rheology EOS defined by correlations, system get some elastic modes of excitations**

Conventional Hydrodynamic Equations

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \rho \mathbf{v} = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \bullet \rho \mathbf{v}\mathbf{v} = \nabla \bullet \mathbf{T} + \rho \mathbf{g}$$

$$\frac{\partial \rho c_m}{\partial t} + \nabla \bullet \rho \mathbf{v} c_m = -\nabla \bullet \mathbf{i}_m + Q_m$$

$$\frac{\partial \rho_e^*}{\partial t} + \nabla \bullet \rho_e^* \mathbf{v} = -\nabla \bullet \mathbf{j}$$

$$\frac{\partial \rho e}{\partial t} + \nabla \bullet \rho \mathbf{v} e = -\nabla \bullet \mathbf{q}_e$$

$$Q_m = \sum_r \nu_{rm} \xi_r ,$$

$$\mathbf{T} = -p\mathbf{I} + \boldsymbol{\sigma}$$

$$e = u + \frac{\mathbf{v}^2}{2}, \qquad \mathbf{q}_e = \mathbf{q} + \mathbf{T} \bullet \mathbf{v}$$

Linear flux-forces relations

$$\mathbf{q} = -\lambda \nabla T + \sum_k \left(h_k + \frac{m_e}{m_k} Z_k h_e \right) \mathbf{i}_k - \frac{5}{2} \frac{kT}{e} \mathbf{j} - \beta \left(\mathbf{E}^* + \frac{\nabla_T \mu_e}{e} \right) - \sum_k \frac{kT}{x_k m_k} D_k^T \mathbf{d}_k,$$

$$\mathbf{j} = \sigma \left[\left(\mathbf{E}^* + \frac{\nabla_T \mu_e}{e} \right) + \alpha \nabla T \right] + \sum_k L_{1k} \nabla_T \tilde{\mu}_k,$$

$$\mathbf{i}_k = \frac{n^2 m_k}{\rho} \sum_{j \neq k} m_j D_{kj} \mathbf{d}_j - \rho D_k^T \nabla \ln T + b_k \rho_k \left(\mathbf{E}^* + \frac{\nabla_T \mu_e}{e} \right).$$

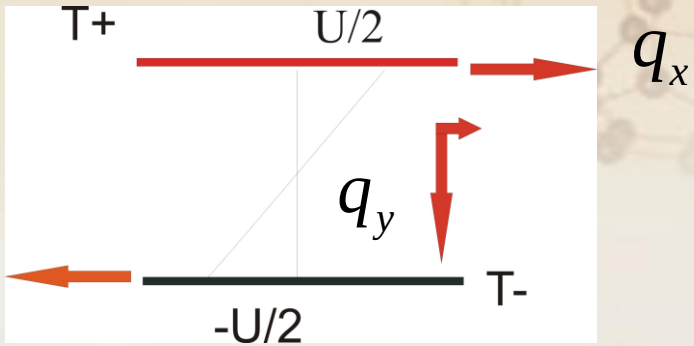
$$\hat{\sigma} = 2\eta \hat{S} = \eta \left(\nabla \mathbf{v} + (\nabla \mathbf{v})^T - \frac{2}{3} \hat{I} \nabla \cdot \mathbf{v} \right)$$

Kuette free molecular flow

Particle distribution functions

$$f_{00}^{+}\left(-\frac{D}{2}, c_y > 0, \mathbf{c}\right) = \frac{n^-}{(2\pi h^-)^{3/2}} \exp\left\{-\frac{(v_x + U/2)^2 + c_y^2 + c_z^2}{2h^-}\right\},$$

$$f_{00}^{-}\left(+\frac{D}{2}, c_y < 0, \mathbf{c}\right) = \frac{n^+}{(2\pi h^+)^{3/2}} \exp\left\{-\frac{(v_x - U/2)^2 + c_y^2 + c_z^2}{2h^+}\right\}.$$



Stress

$$\sigma_{xy} = -m\int c_x c_y f^+ d\mathbf{c} - m\int c_x c_y f^- d\mathbf{c} = mn\frac{4}{\sqrt{\pi}}\sqrt{h^+h^-}S_1,$$

$$S_1 = U/\sqrt{h^+h^-}$$

Heat flux

Fourier Law against grad T

$$q_y = -\frac{4mn}{\sqrt{2\pi}}(\sqrt{h^+} - \sqrt{h^-})\sqrt{h^+h^-}(1 + 2S_1^2).$$

Heat flux normal to grad T
Does not exist in hydrodynamics,
But could exist in turbulent flow !!!

$$q_x = -\frac{\sqrt{\pi}}{2}S_1\frac{5 + 8S_1^2}{1 + 2S_1^2}q_y.$$

BE solution at arbitrary Kn number

$$\tau v_y \frac{df^+(y)}{dy} = f_0^+(y) - f^+(y), \qquad -\tau |v_y| \frac{df^-(y)}{dy} = f_0^-(y) - f^-(y).$$

$$ds = \sqrt{2h(y)}dy/Al|v_y|.$$

$$f(s(y)) = f_0^+(-D/2)e^{-\int_{s(-D/2)}^{s} ds'} + \int_{-s(D/2)}^{s} f_0^+(s')e^{-\int_{s'}^{s} ds''}ds' +$$

$$+ f_0^-(D/2)e^{-\int_{s}^{s(D/2)} ds''} + \int_{s}^{s(D/2)} f_0^-(s')e^{-\int_{s}^{s'} ds''}ds'.$$

$$\sigma_{xy}(y) = \left[U(y) + \frac{U}{2}\right] mn^- \left(\frac{2h^-}{\pi}\right)^{1/2} \int_0^\infty zF^+\left(z, y, -\frac{D}{2}\right) dz +$$

$$+ \int_{-D/2}^{y} [U(y') - U(y)] mn(y') \left(\frac{2h(y')}{\pi}\right)^{1/2} \int_0^\infty F^+(z, y, y') dz \frac{dy'}{Al} +$$

$$+ \left(U(y) - \frac{U}{2}\right) mn^+ \left(\frac{2h^+}{\pi}\right)^{1/2} \int_0^\infty zF^-\left(z, y, \frac{D}{2}\right) dz +$$

$$+ \int_{y}^{D/2} [U(y') - U(y)] mn(y') \left(\frac{2h(y')}{\pi}\right)^{1/2} \int_0^\infty F^-(z, y, y') dz \frac{dy'}{Al},$$

$$F^+(z, y, y') = \exp\left\{-z^2 - \int_{y'}^{y} \left(\frac{h(y'')}{h(y')}\right)^{1/2} \frac{dy''}{|z|Al}\right\},$$

$$\sigma_{xy}(y) = -m \int (v_x - U(y)) v_y f(s(y)) d\mathbf{v},$$

$$F^-(z, y, y') = \exp\left\{-z^2 - \int_{y}^{y'} \left(\frac{h(y'')}{h(y')}\right)^{1/2} \frac{dy''}{|z|Al}\right\},$$

Onuphriev A, Sapharov R., Son K. Son E. Semiempirical models of turbulence, Theory and Experiment, Russia 2003, Begell House, 2009

Free molecular, Hydrodynamics Turbulent flows

- Low Knudsen number flows – no Flux-Forces Irreversible Thermodynamics
- Hydrodynamics – Linear constitutional relations
- Turbulent
  - no Fluux – Flow linear relations
  - Size effects in transport
  - Negative thermal conductivity and viscosity
  - TURBULENT-FREE FLOW are same

Multiphase Coulomb Systems

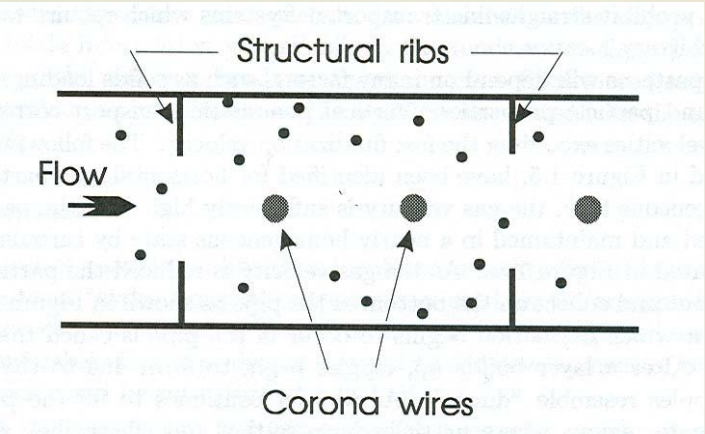


Figure 1.3: Electrostatic precipitator.

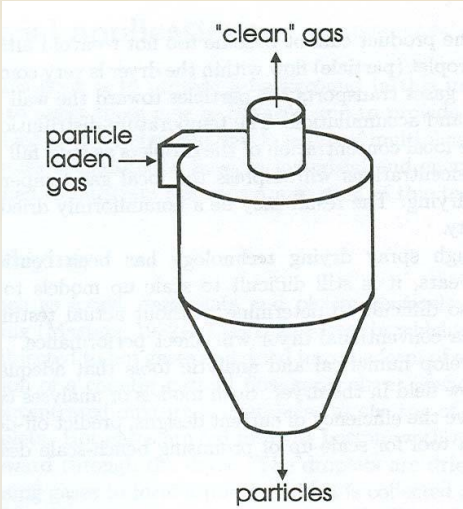


Figure 1.2: Cyclone separator.

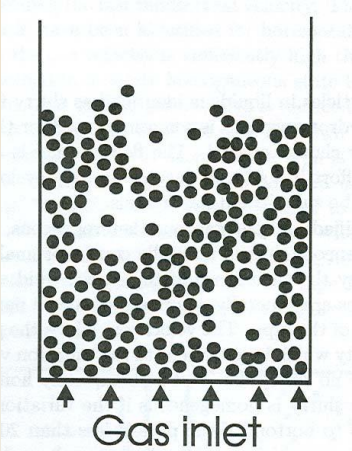


Figure 1.6: Fluidized bed.

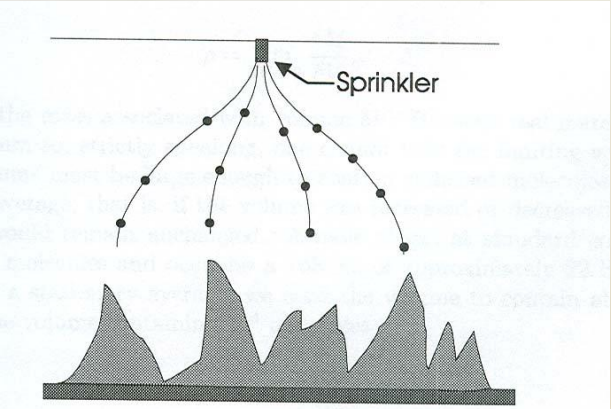


Figure 1.12: Ceiling sprinkler fire suppression system.

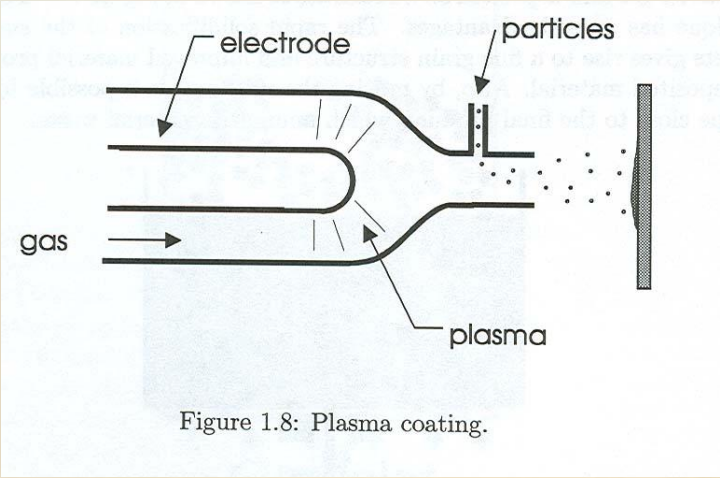


Figure 1.8: Plasma coating.

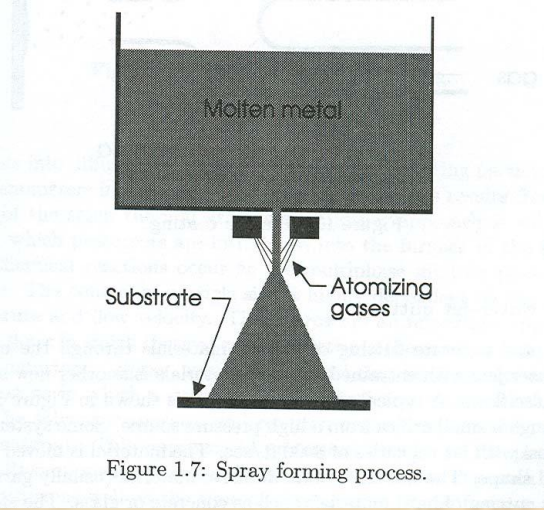


Figure 1.7: Spray forming process.

Multiphase Coulomb Hydrodynamics

- **Nondivided multiphase fluids: superfluidity and «normal fluid».**
- **Dusty plasma viscosity (If Newtonian).**
- **Multiphase plasma systems (Coulomb systems with boundary)**
  - Plasma phase transition
  - Electric discharges with liquid electrodes
  - vortexes and turbulence
  - Dusty plasma
  - Sonoluminescent plasma
  - Raylegh-Taylor Instability and Turbulent miximg
- **Quantum Density Functional method in hydrodynamics of Colounb systems**
- **Space charge electro neutral sheets**
- **Electron beams in plasma, Degradation spectra**
- **Laser Hydrodynamics**

RHEOLOGY Viscous-Plastic Media

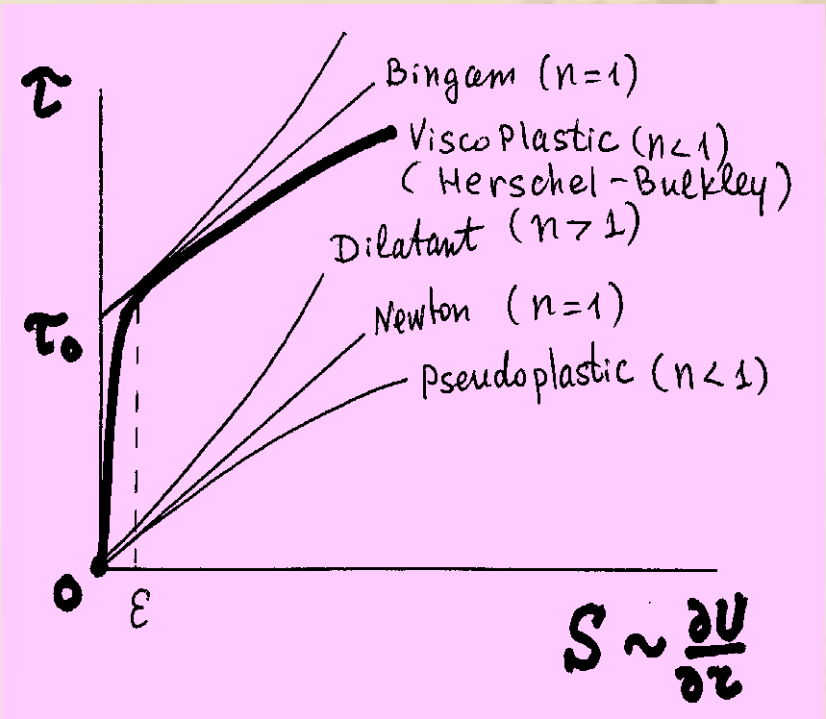
$$\frac{\partial \rho}{\partial t} + \nabla \bullet \rho \mathbf{v} = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \bullet \nabla \mathbf{v}\right) = -\nabla p + \nabla \bullet \boldsymbol{\tau} + \rho \mathbf{g}$$

$$\boldsymbol{\tau} = 2\mu \mathbf{S}$$

$$S_{ik} = \frac{1}{2}\left(\frac{\partial \mathrm{v}_i}{\partial \mathrm{x}_k} + \frac{\partial \mathrm{v}_k}{\partial \mathrm{x}_i} - \frac{2}{3}\delta_{ik}\frac{\partial \mathrm{v}_l}{\partial \mathrm{x}_l}\right)$$

$$p = p_0 + E\frac{\rho - \rho_0}{\rho_0}$$



$$\boxed{\sigma_{ik} = 2\left(\tau_0 S^{-1} + \mu_0 S^{n-1}\right) S_{ik}} \qquad \boxed{\tau \geq \tau_0}$$

$$S^2 = \frac{1}{2}\mathbf{S}:\mathbf{S}$$

$$\boxed{S_{ik} = 0} \qquad \boxed{\tau < \tau_0} \qquad \tau^2 = \frac{1}{2}\boldsymbol{\tau}:\boldsymbol{\tau}$$

Boundary conditions: $p\big|_{\Gamma_{x=0}} - p\big|_{\Gamma_{x=L}} = \Delta p, \quad u_a\big|_{\partial S} = 0$

Pipe or plane parallel Rheology flow

Rheological model of Herschel-Bulkley fluid is described by the following equations:

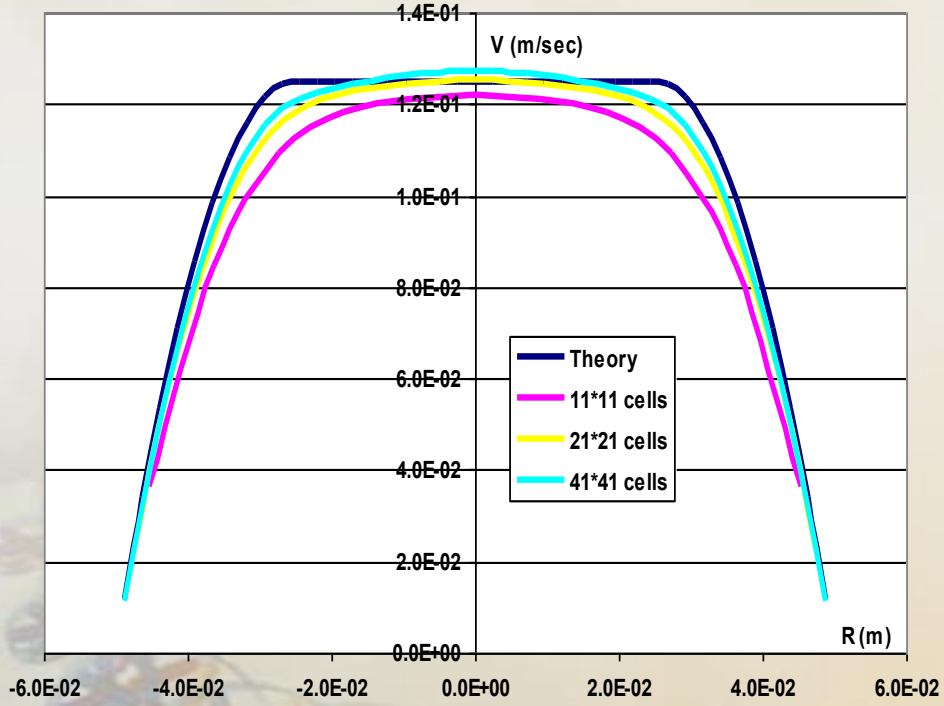
$$\tau_{ij} = \left(\tau_0 \, \dot{\gamma}^{-1} + \mu_0 \, \dot{\gamma}^{n-1} \right) \dot{\gamma}_{ij} \quad \text{, for} \quad \tau \geq \tau_0$$

$$\dot{\gamma}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

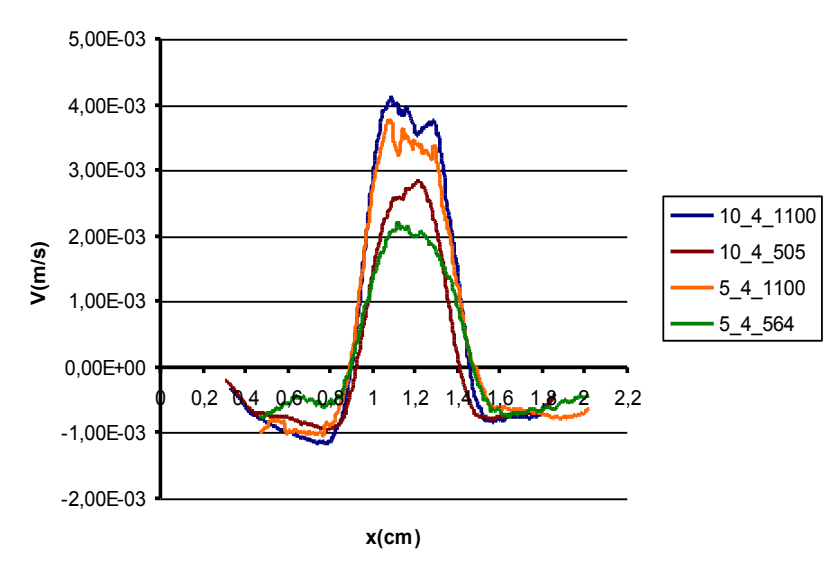
$$\dot{\gamma}_{ij} = 0 \quad \text{, for} \quad \tau < \tau_0$$

$$\dot{\gamma} = \sqrt{2^{-1} \, \dot{\gamma}_{ab} \, \dot{\gamma}_{ab}} \quad , \quad \tau = \sqrt{2^{-1} \, \tau_{ab} \, \tau_{ab}}$$

Velocity profile of SCCS at strong correlation regime and Dusty plasma



Bingham and Hershel-Bulkley flows (3D pipe) n

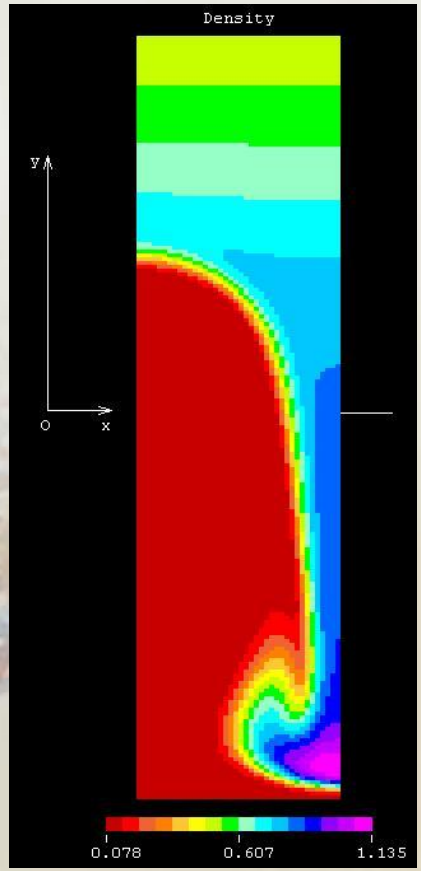


Velocity distribution for Dusty plasma (Fortov V., Gavrikov A.Petrov, e.o. 2006)

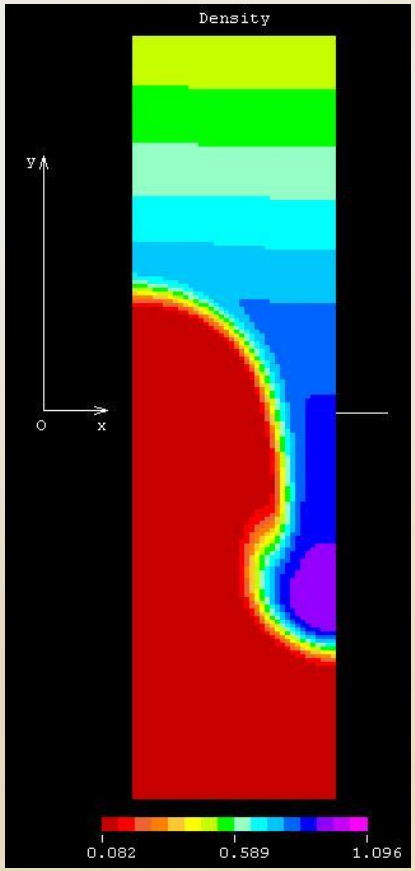
Influence of viscosity to the flow

Newtonian fluid is considered . A series of numerical calculations with gradually increasing viscosity has been made.

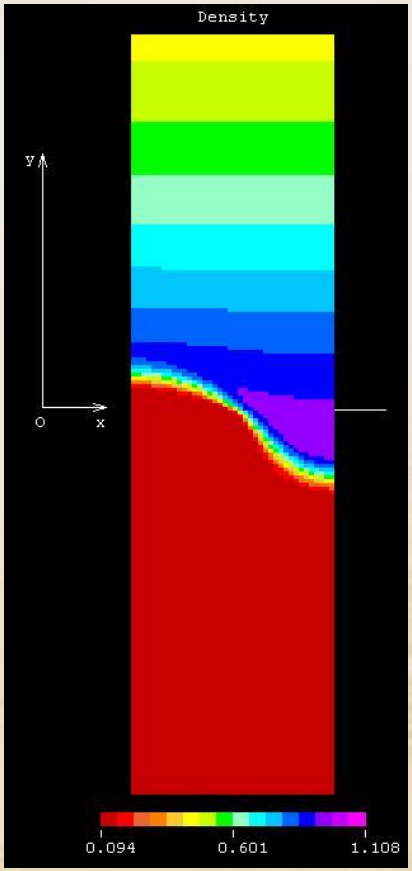
1) $vis = 0.1$



2) $vis = 0.2$



3) $vis = 0.5$

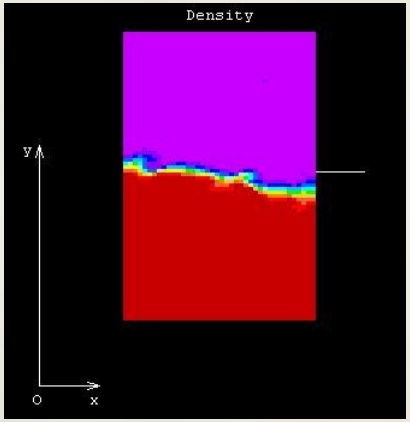


Influence of rheology

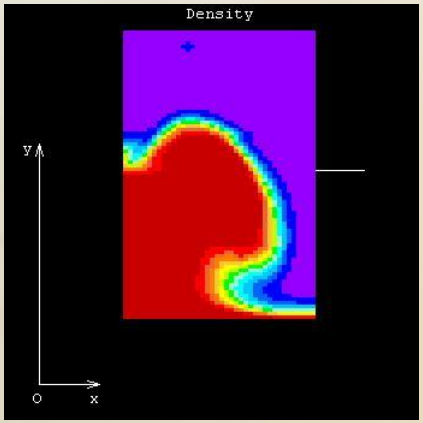
A series of numerical calculations with various $\dot{\gamma}_{\min}$ and τ_0 has been made.

1) $\dot{\gamma}_{\min} = 10^{-4},\ \tau_0 = 0.05,\ vis = 0.01$

a) time = 3.4

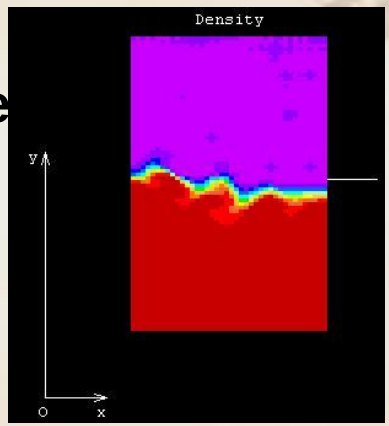


b) time = 10

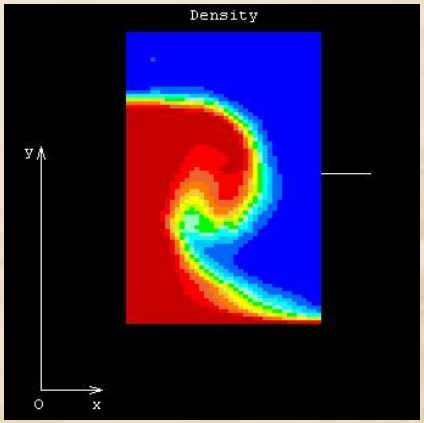


2) $\dot{\gamma}_{\min} = 10^{-4},\ \tau_0 = 0.1,\ vis = 0.01$

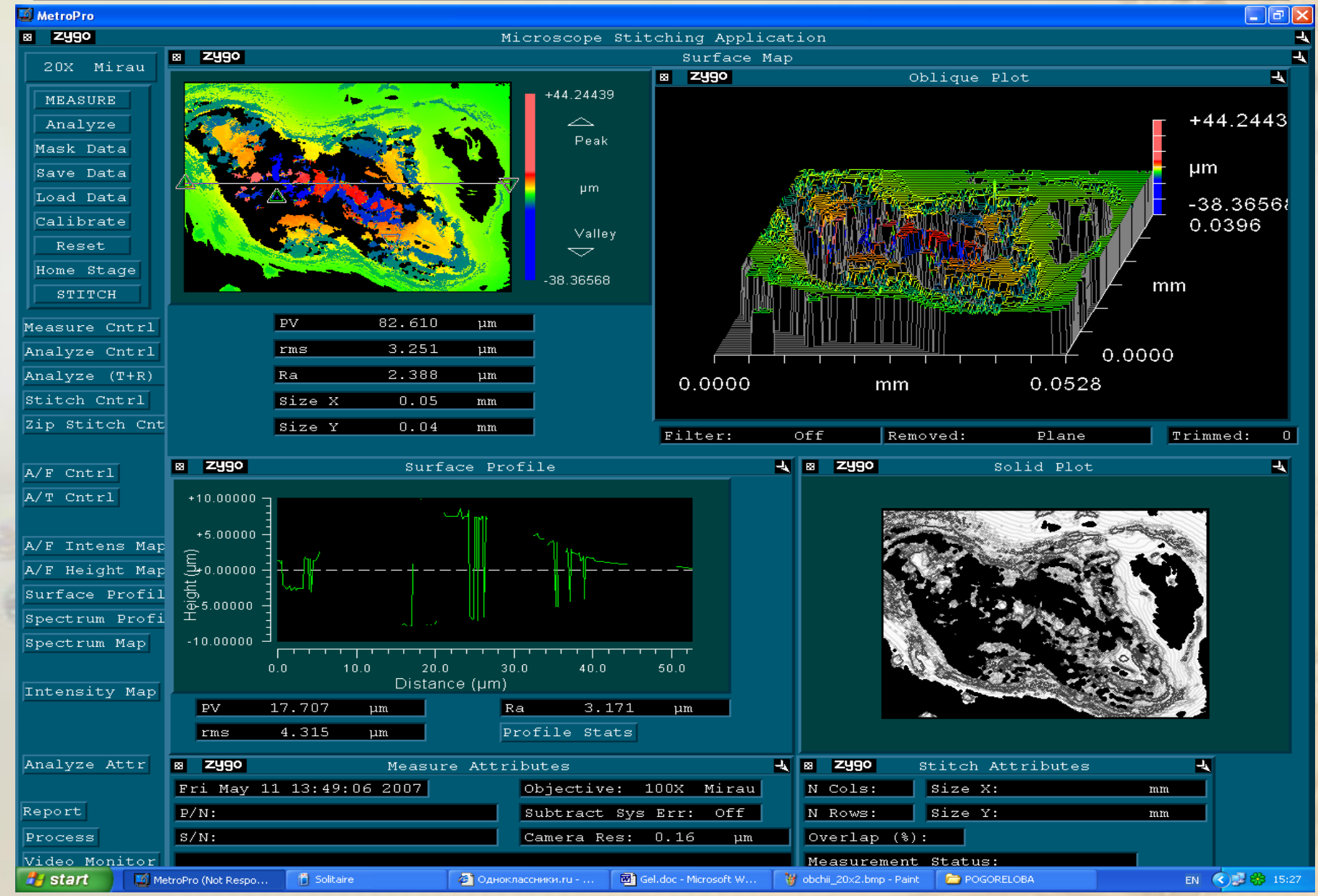
a) time



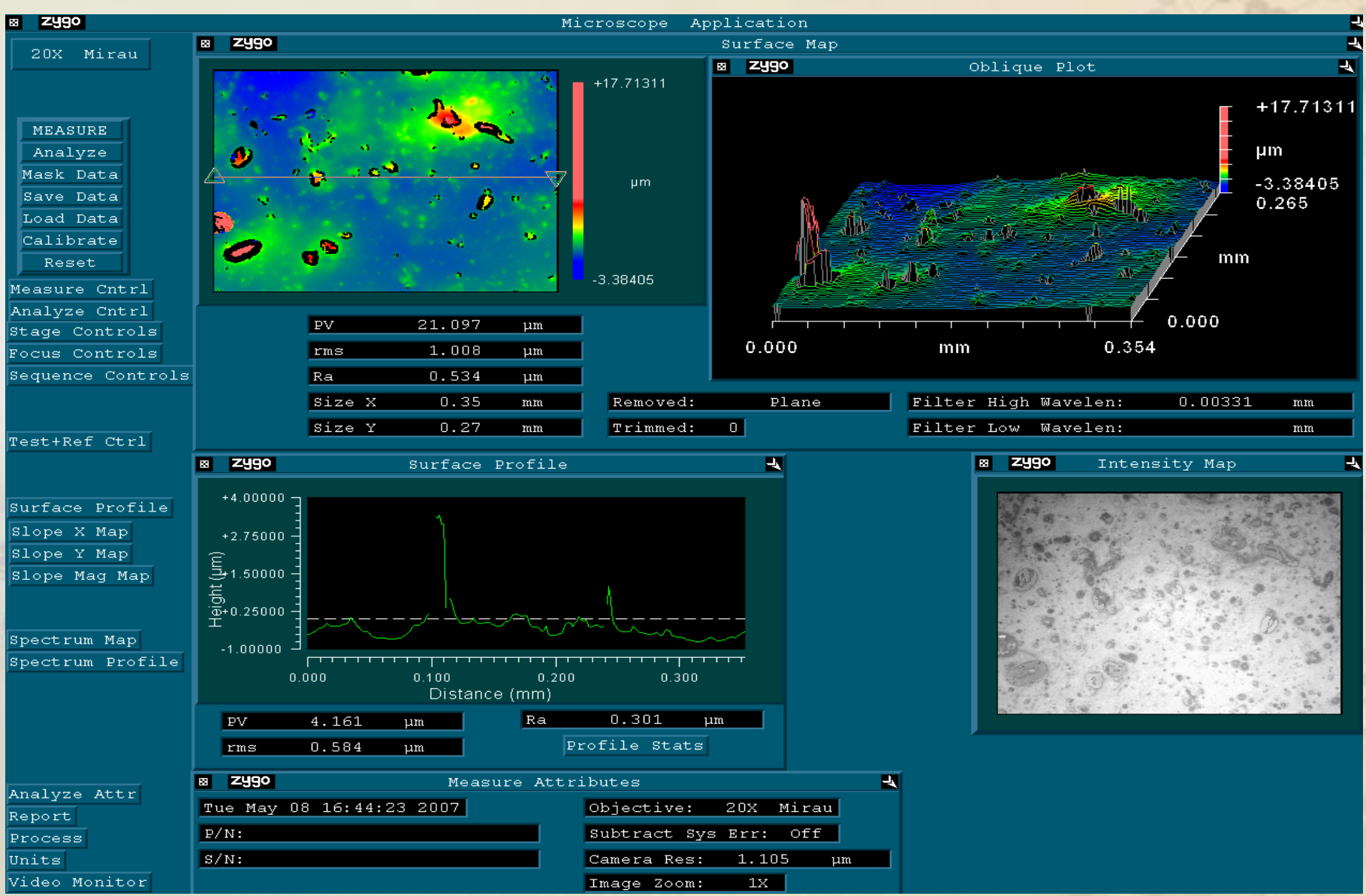
b) time = 10



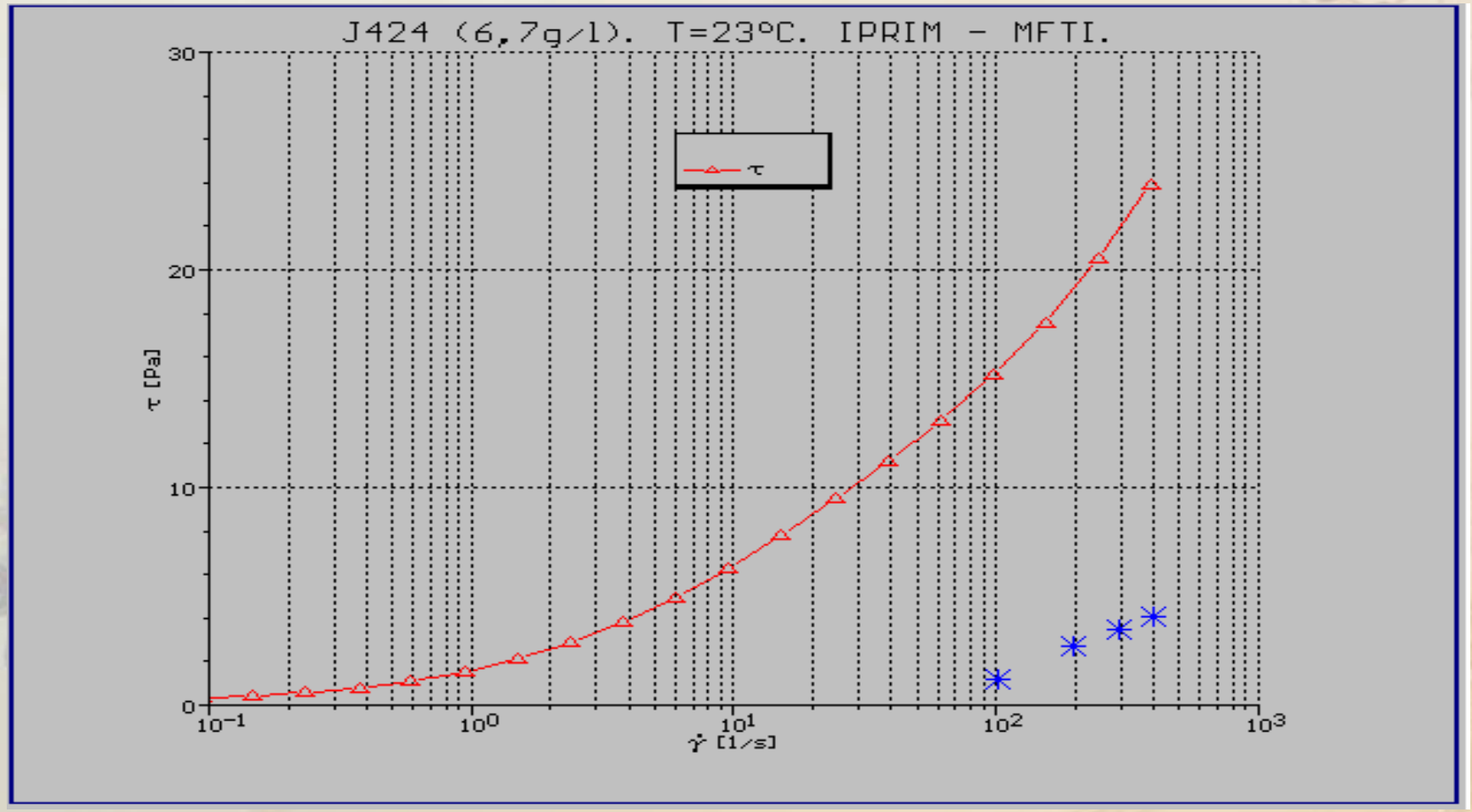
Rheology simulation of SCCS by Gel (long chains similar to long correlations)



Micro- structure VPF similar to Dusty Plasma



Micro-rheology analysis
(For low mechanical limit stress there is strong dependence on initial conditions – phase transition indicator)



Kuette free molecular flow

Particle distribution functions

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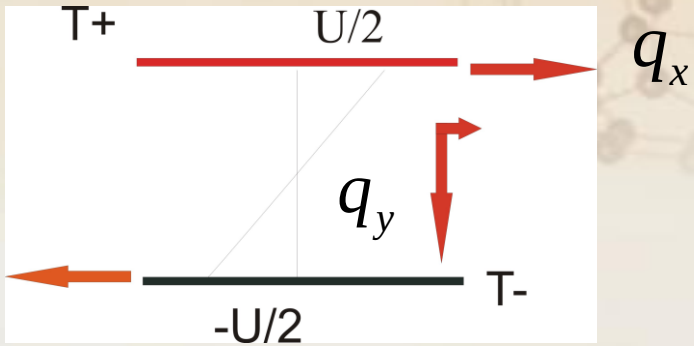

Stress

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$$S_1 = U/\sqrt{h^+h^-}$$

Heat flux

Fourier Law against grad T

$$q_y = -\frac{4mn}{\sqrt{2\pi}}(\sqrt{h^+} - \sqrt{h^-})\sqrt{h^+h^-}(1 + 2S_1^2).$$

Heat flux normal to grad T
Does not exist in hydrodynamics,
But could exist in turbulent flow and SCCS and Dusty plasma flow

$$q_x = -\frac{\sqrt{\pi}}{2}S_1\frac{5 + 8S_1^2}{1 + 2S_1^2}q_y.$$

Phase Indicator Method for 2 phase system for the Coulomb systems

Time scales hierarchy in hydrodynamics

Moment equations

$$M_i = \langle v_i \rangle, \qquad M_{ij} = \langle v_i v_j \rangle, \qquad M_{ijk} = \langle v_i v_j v_k \rangle,$$

$$M_{ijkl} = \langle v_i v_j v_k v_l \rangle, \qquad \frac{d}{dt} = \frac{\partial}{\partial t} + V_k \frac{\partial}{\partial x_k}$$

$$\tau_1 = \tau_h : \qquad \frac{dM_i}{dt} = P_i - \frac{\partial M_{ij}}{\partial x_j} + \nu \Delta M_i$$

$$\tau_2 << \tau_1 : \qquad \frac{dM_{ij}}{dt} = P_{ij} - \varepsilon_{ij} + \Phi_{ij} - \frac{\partial M_{ijk}}{\partial x_k} - \frac{\partial q_{ijk}}{\partial x_k} + \nu \Delta M_{ij}$$

$$\tau_3 << \tau_2 : \qquad \frac{dM_{ijk}}{dt} = P_{ijk} - \varepsilon_{ijk} + \Phi_{ijk} - \frac{\partial M_{ijkl}}{\partial x_l} - \frac{\partial q_{ijkl}}{\partial x_l} + 3\nu \Delta M_{ijk}$$

Phase Indicator Method
(Chandrasekhar, Drew [D83], Lundgren [JL90], Fergusson, Poppinet [FP96], Son[2000].

Phase variables

$$\varphi_{\mathbf{a}}(\mathbf{r},t) = \Theta(\mathbf{r} - \mathbf{r}_{\mathbf{Sa}}(t)), \mathbf{r}_{\mathbf{S}}(t) \in R_{\mathbf{a}}^3$$

$$\frac{\partial \varphi_{\mathbf{a}}}{\partial t} + \mathbf{D}_{\mathbf{a}} \bullet \nabla \varphi_{\mathbf{a}} = 0$$

$$\nabla \varphi_{\mathbf{a}} = \mathbf{n}_{\mathbf{a}} \delta(\mathbf{r} - \mathbf{r}_{\mathbf{Sa}}(t))$$

Generaized Transport Equation

$$\frac{\partial \varphi_{\mathbf{a}} \rho \xi}{\partial t} + \nabla \bullet \varphi_{\mathbf{a}} \rho \rho \mathbf{v} \xi = -\nabla \bullet \varphi_{\mathbf{a}} \mathbf{i}_{\xi} + \varphi_{\mathbf{a}} Q_{\xi} + \rho(\mathbf{v}_{\mathbf{a}} - \mathbf{D}_{\mathbf{a}}) \xi_{\mathbf{a}} \bullet \nabla \varphi_{\mathbf{a}} + \mathbf{i}_{\xi} \bullet \nabla \varphi_{\mathbf{a}}$$

Modified Transport Equations

$$\frac{\partial \varphi_{\mathbf{a}} \rho}{\partial t} + \nabla \bullet \varphi_{\mathbf{a}} \rho \mathbf{v} = \rho(\mathbf{v}_{\mathbf{a}} - \mathbf{D}_{\mathbf{a}}) \bullet \nabla \varphi_{\mathbf{a}}$$

$$\frac{\partial \varphi_{\mathbf{a}} \rho \mathbf{v}}{\partial t} + \nabla \bullet \varphi_{\mathbf{a}} \rho \mathbf{v}\mathbf{v} = \nabla \bullet \varphi_{\mathbf{a}} \mathbf{T} + \varphi_{\mathbf{a}} \rho \mathbf{g} + [\rho(\mathbf{v}_{\mathbf{a}} - \mathbf{D}_{\mathbf{a}}) \mathbf{v}_{\mathbf{a}} - \mathbf{T}] \bullet \nabla \varphi_{\mathbf{a}}$$

$$\frac{\partial \varphi_{\mathbf{a}} \rho c_m}{\partial t} + \nabla \bullet \varphi_{\mathbf{a}} \rho \mathbf{v} c_m = -\nabla \bullet \varphi_{\mathbf{a}} \mathbf{i}_m + \varphi_{\mathbf{a}} Q_m + \mathbf{i}_m \bullet \nabla \varphi_{\mathbf{a}}$$

$$\frac{\partial \varphi_{\mathbf{a}} \rho e}{\partial t} + \nabla \bullet \varphi_{\mathbf{a}} \rho \mathbf{v} e = -\nabla \bullet \varphi_{\mathbf{a}} \mathbf{q}_e + \mathbf{q}_e \bullet \nabla \varphi_{\mathbf{a}}$$

Coulomb correlations and averaging

Filtered equations

$$< A > (\mathbf{r},\mathbf{v}) = \int A(\mathbf{r}',\mathbf{v}')g(\mathbf{r}-\mathbf{r}',\mathbf{v},\mathbf{v}')d\mathbf{r}'$$

$$g(\mathbf{r}-\mathbf{r}',\mathbf{v},\mathbf{v}') = f_{corr}(x-x'/L_x, y-y'/L_y, z-z'/L_z, \mathbf{v},\mathbf{v}')$$

$$< \mathbf{u}_a(\mathbf{r},t)\bullet\mathbf{n}\delta(\mathbf{r}-\mathbf{r}') >= u_{an}(\mathbf{r}_{\mathbf{sa}})\omega(\mathbf{r}-\mathbf{r}_{\mathbf{Sa}})$$

Averaged equations

$$\varphi_a =< \varphi_a > +\varphi_a^{'}, \mathbf{v}_a =< \mathbf{v}_a > +\mathbf{v}'$$

$$\Phi_a =< \varphi_a(\mathbf{r}(t) > \rightarrow 0 < \Phi_a < 1, \mathbf{V}_a =< \mathbf{v}_a >$$

$$\varphi_a\mathbf{v}_a = \mathbf{u}_a, \varphi_a = \varphi_a^2$$

$$\frac{\partial\Phi_a}{\partial t} + < \mathbf{D}_a > \bullet\nabla\Phi_a = -< \mathbf{D}'\bullet\nabla\varphi_a^{'} >$$

$$\rho_a\left(\frac{\partial\mathbf{U}_a}{\partial t} + \nabla\bullet\mathbf{U}_a\mathbf{U}_a\right) = \nabla\bullet < \varphi_a\mathbf{T} > -\rho_a\nabla\bullet < \mathbf{u}_a^{'}\mathbf{u}_a^{'} > +\rho_a\Phi_a\mathbf{g} + < [\rho_a(\mathbf{u}_a - \mathbf{D}_a)\mathbf{u}_a - \mathbf{T}]\bullet\nabla\varphi_a >$$

2-particle correlation (Green) function

- Analytical theory based on perturbation theory.
- Group expansion, resummation by ring and ladder diagrams, result depend on the order of resummation.
- MD simulation – known results and new in the progress.
- Experimental results (Dusty plasmas, 2D systems, e.o.)

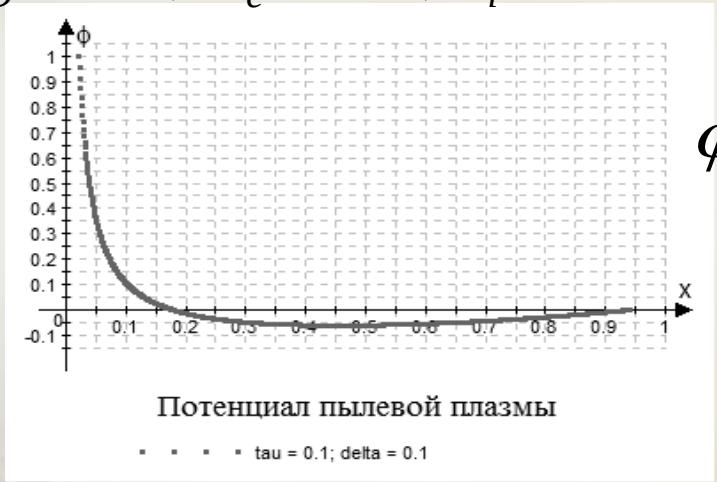
Nonhydrodynamic Dusty plasma properties

- Thermodynamic and screening in a plasma with nonthermal dusty particles
- Hydrodynamic and kinetic methods CDP description
- DP Kinetic Dynamic Screening in open system
- DP Hydrodynamic Screening in open system
- Hydrodynamic DP Description
- DP shear flows, «skew» fluxes (CDP Kn<1)
- Hydrodynamics of CDP as Multiphase Dusty System (Phase variables)
- Viscous-elastic properties of DP and Plasma Crystal
- CDP Instabilities: Hydrodynamic, Thermal, Acoustic, Plasma-chemical and
- DP Hydrodynamic Instabilities in Kinetic Approximation
- CDP nonlinear stage DP Instabilities, vortexes, cascades
- Shock waves in DP

Existence of Attractive Potential between positively charged particles in Pure Coulomb System not in thermal equilibrium

$$Z = 10^4,\ \delta = 1/100 \qquad \nabla \bullet E = -\Delta\Phi = 4\pi\rho_e^*$$

$$n_D = 10^3,\ n_e = 10^7,\ n_i = 10^5 \qquad \rho_e^* = Ze\delta(r) - n_{e0}e^{e\Phi/kT_e} + n_{i0}e^{-e\Phi/kT_i} + Zn_D f(r,T)$$



$$\varphi_0 = -\frac{\tau}{1+\tau}\ln\left(\frac{1}{\delta}\right)$$

Starostin, Fillipov – pure repulsion in fully Equlibrium plasma

DP with positive charge Z=10000

Due to high Z electrons are close to DP

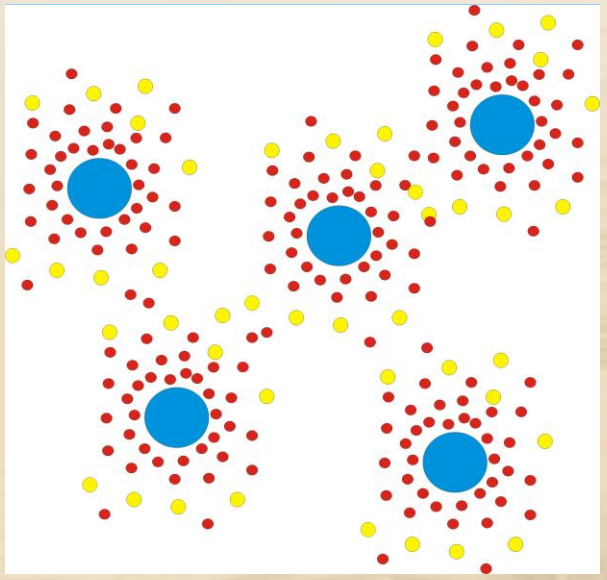
Their number more than Z, the rest for ion screening

The net charge DP and e-dressing become negative

Ions gradually compensate negative charge

At WZ-length (distance between DP) potential remains low negative

At more distance DP gives full screening

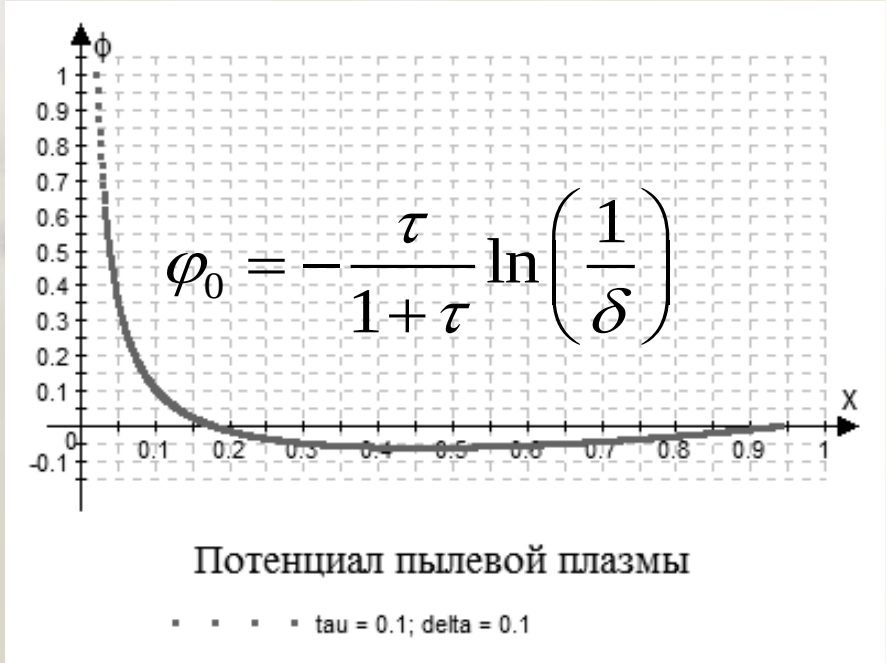


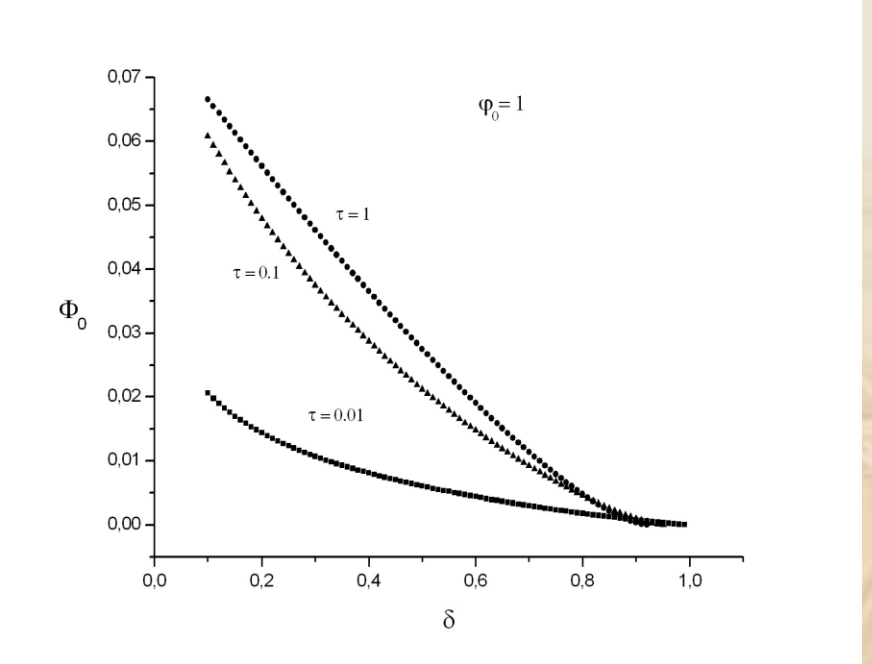
Nonlinear Piosson-Boltzmann equation for nonthermal DP

$$-\Delta\Phi = 4\pi(n_i - n_e) = 4\pi n_{eo}(\delta e^{-e\Phi/kT_i} - e^{-e\Phi/kT_e})$$

$$\delta = \frac{n_{i0}}{n_{e0}},\ \tau = \frac{T_i}{T_e},\ \varphi = \frac{e\Phi}{kT_e},\ x = \frac{r}{r_{De}},\ \Phi_0 = \Phi(R_D),\ \Phi(R_{WZ}) = 0$$

$$\frac{1}{x^2}\frac{d}{dx}\left(x^2\frac{d\varphi}{dx}\right) = \exp(\varphi) - \delta\cdot\exp(-\frac{\varphi}{\tau}),\quad \varphi(a) = \varphi_0,\quad \varphi(b) = 0$$





Conclusion

- Nonideal plasma in transition to crystallization become high correlated and constitutional relations changes depending on the problem under consideration.
- In plane parallel flows with different temperatures the thermal flux no parallel to temperature gradient may exist
- Nonideal plasma REOS become Non NewtonIan, in transition to crystal it has elastic behavior.
- In Complex plasma wich is not in full thermodynamic equilibrium (very often in DP experiments) the potential could be attractive which become fully repulsive in the limit of full thermal equilibrium
- In some models the existing of plasma crystal is defines by limiting size or wall potential, this approach need consider nonhydrodynamic behavior and viscous – elastic properties of Dusy Plasma
- Limited number of particles in experiments nedds consider thermodynamic limts and behavior plasma size effects
- Hydrodynamic Density Functional could be applied to the system
- Quark – Gluon plasma has the same behavior due to same Hydrodynamic approach and finite number of collidung heavy ions in available experiments