Electrokinetic aspects of turbulent drag reduction in surfactant solutions

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Electrokinetic mechanism of drag reduction of turbulent flow of surfactant solutions is proposed. The surfactant micelles with surface charge attract ions of the solvent or counterions, forming an electric double layer. The ions in the layer are “frozen” in a strongly bonded structure, which reduces the local flow around micelle. The local flow is the strain of small turbulent scale fluctuation. Numerical example indicates that electrokinetic mechanism supplies a reasonable explanation of the drag reduction in surfactant solutions. The proposed model is only the preliminary one, which points on the electrokinetics as an additional mechanism which contributes to the hydrodynamics of surfactant solutions. © 2004 American Institute of Physics.

I. INTRODUCTION

Drag reduction is a phenomenon by which small amounts of additives can greatly reduce the turbulent friction factor of a fluid. It can be used to reduce energy consumption of pumping, increase flow rate, and decrease the sizes of pumps, pipes, and fittings in flow systems. Very wide review of the phenomenon was done by Zakin, Lu, and Bewersdorff and by Gyr and Bewersdorff. One of the most important conclusions is that the drag reduction in surfactant solutions occurs always when the surfactant molecules form rod-like micelles. The drag reduction in turbulent flow expresses itself in friction reduction, change of velocity profile, and the structure of turbulence. The maximum friction reduction has been found for polymer solution is presented by Virk’s asymptote. For surfactants the friction factor may be lower. Results of turbulent viscosity profile are reported in both channel and pipe flows. Hetsroni et al. achieved in tube flow drag reduction well below the predictions of Virk’s asymptote. Turbulence intensity profiles in drag reducing surfactant solutions were reported by Povkh et al., Bewersdorff and Ohlendorf, Chara et al., and Beisdorfer et al. A drastic reduction of transverse turbulence intensity was observed in surfactant solution in comparison with to Newtonian fluid. Chara et al. and Hetsroni et al. using Habon G surfactant obtained drag reduction greater than that predicted by Virk’s asymptote. Strong reduction of the Reynolds stresses was observed by Povkh, Gyr and Bewersdorff, and Massah and Hanratty.

The effect of drag-reducing additives on the structure of wall turbulence was investigated by Hetsroni et al. The results of spanwise streak spacing indicated that wall shear velocity may be an appropriate parameter for describing streak spacing behavior in drag reduced flows. Few works indicate an increase of shear viscosity and its change by the presence of salts.

Several hypotheses of the drag reduction mechanism have been suggested but none of them propose complete explanation of drag reduction of surfactant solutions. Goldshtik et al. proposed a theory of a viscous layer in near-wall turbulent flow of drag-reducing fluids. The conjunction conditions of the outer boundary of a viscous layer with the asymptotic velocity and fluctuation energy profiles were formulated based on experimental data. The model was developed for Maxwell and Oldroyd media and does not cover a variety of drag reduction fluids and, especially, does not take into account any influence of ions charge. The change of shear viscosity was theoretically studied by Doi and Edwards, which established an equation for the viscosity of a dilute rod-like solution.

In the present work an electrokinetics explanation of the interaction of surfactant micelles and turbulent flow is presented. A single micelle with a charged surface interacts with the surrounding ions. The ions are attracted by electrical forces arranging in so-called electric double layer (EDL). The EDL consists of two layers: Stern layer where ions opposite in charge to surface charge are effectively immobilized due to strong interaction with the surface; and Gouy–Chapmen layer with diffuse mobile ions and the same sign of electric charge as in the Stern layer. When the system, micelle, and the layer of ions, is freely moving in a turbulent flow, the local flow around a micelle can be considered as a combination of a rigid body rotation and strain. In coordinates rotating with a micelle, the flow is a strain flow and ions are moving with the flow only in the angular direction, while in the radial direction the motion is significantly reduced because of strong electrical forces. The ions concentrate in regions where the angular flow velocity is small. Here the ions, because of friction interaction with the flow, reduce the flow velocity and, therefore, the turbulent fluctuation.

The proposed model is valid only for charged surfactant in solutions with low concentration of salt ions. At very high concentration of these ions the potential reduces even to zero and the electrokinetic effect does not work anymore.

II. ELECTRICAL FIELD AROUND A MICELLE

There are three types of surfactant molecules from the point of view of electrical properties: anionic, cationic, and...
This paper deals with the first two kinds of surfactants. At low concentration the surfactant solution comprises of charged monomers, which together with counterions are distributed homogeneously in the solvent. In such solvents, the electrical field induced by surfactant charged molecules and counterions is zero and no mean electrical force acts on the molecules. When the concentration of the surfactants is above their critical concentration, so-called Kraft point, the surfactant molecules form assemblies called micelles, in which the nonpolar, hydrophobic portions concentrate in the center while the polar, hydrophilic ends form a surface. The geometrical form of the micelles depends of the surfactant concentration. At lower concentration, surfactant molecules aggregate together forming spherical micelles, while at higher concentration rod-like micelles are formed. The micelles are usually composed of 20–1000 monomers. The size of rod-like micelles is close to the upper number. Assuming the charge of a charged monomer to be one electron, the charge of a single rod-like micelle is somewhere in the range of \(200e^{–}1000e\). The same amount of opposite charges carrying by counterions surrounds a micelle (see Fig. 1). In fact, the salt ions always exist in the solvent and in many cases their amount can be even higher than that of counterions. The charge of micelles depends on the charge of surfactant molecules. In case of nonionic surfactants the charge of the surface is zero. But even in this case and in the case of other types of additives, such as fibrous or polymer molecules, a nonzero \(\zeta\) potential can exist, which can generate the same effect.

It was found that drag-reducing surfactant solutions always contain rod-like micelle. Therefore, only rod-like micelles or any other fibrous additives are discussed in this work. Consider a single rod-like micelle surrounded by others and all are assumed oriented in the same direction (see Fig. 2). The micelles are distributed, on the average, homogeneously in the space. Each micelle is surrounded by others, on the average, at the same distance \(2R\). Because the concentration of micelles is low and the distance between any two micelles is large, relative to their size, the electrostatic field induced by the micelles depends mostly on the surface charge and the distance between the micelles and not on their relative orientation. This is the reason why the proposed model supposes that all micelles are oriented in the same direction.

Consider a single cell of volume \(V\) and radius \(R\) with a micelle in the center (see Fig. 3). These geometrical parameters of a single cell depend on the micelle concentration in the solvent. The charged micelle induces an electrostatic potential. Because the imaginary boundary of the cell is at almost the same distance from surrounding micelles, the electrical potential can be assumed to be uniform on the imaginary outer boundary and equal to zero. The boundary conditions for the electrostatic potential \(\varphi\) are

\[
\varphi = \varphi_0 \quad \text{at} \quad r = a, \\
\varphi = 0 \quad \text{at} \quad r = R,
\]

where \(\varphi_0\) is the surface potential or \(\zeta\) potential of a micelle. The electrostatic potential at any point in the space of the unit cell is related to the number of electrostatic charges per unit volume by the Poisson equation

\[
\frac{d^2\varphi}{dr^2} = -\frac{enze(r)}{\varepsilon_\infty \varepsilon_0},
\]

where \(n(r)\) — the concentration of ions, \(z\) — the valence of ions, \(e\) — the electron charge, \(\varepsilon\) — dielectric constant of the medium, and \(\varepsilon_\infty\) — the permittivity of vacuum.
The surface charge is further assumed to be positive. The number concentration of ions of each type at some point is given by the Boltzmann equation

\[ n^-(r) = n_0^- e^{-\alpha \varphi(r)}, \]

and

\[ n^+(r) = n_0^+ e^{-\alpha \varphi(r)}. \]

Their net charge density is

\[ \varepsilon_0 \varepsilon \kappa E(r) = \varepsilon_0 \varepsilon \kappa E(r), \]

These ions surrounding a micelle under the influence of the electric field establish an electric double layer. In the compact layer the ions are strongly attracted to the micelle surface and are immobile. In the diffuse double layer the ions are affected less by the electrical field and are mobile. We do not consider the interaction of the surrounding charge on the electrical field inside a micelle. This interaction might reduce the connection between molecules in a micelle, as well as change the surface potential of a micelle. Anyway, if one can measure the \( \zeta \) potential of micelles in a solvent, it provides all needed information.

Two extreme cases are considered: equal number of positive and negative ions in the solvent, and only one type of charged counterions in the solvent. The first case takes place when the concentration of salt ions is higher than the concentration of surfactants and the effect of surfactant counterions can be neglected relative to the effect of salt ions. The second case takes place when the concentration of salt ions is low relative to the concentration of surfactants and only the surfactant counterions can be assumed to exist around the surfactant micelles.

(a) The nondimensional Poisson–Boltzmann equation in the case of equal concentration of positive and negative charged ions surrounding micelles is

\[ \varepsilon_0 \varepsilon \kappa E(r) = \kappa^2 \sinh(\varphi), \]

\[ \frac{d^2 \varphi}{dr^2} + \frac{1}{r} \frac{d \varphi}{dr} = \kappa^2 \sinh(\varphi), \]

where

\[ \varphi = \varphi_0 e^{\kappa \varphi}; \quad \varphi_0 = k_0 T; \quad \varphi = \varepsilon_0 \varepsilon \kappa E(r); \quad \varphi = \kappa \varphi \kappa; \quad \varphi = \kappa \varphi \kappa. \]

Here \( l^* = R, \) and \( \kappa = l^*/D, \) where \( D \) is the characteristic length called Debye length

\[ D = \left( \frac{\varepsilon_0 \varepsilon_0 k_B T}{2 n_0^2 e^2} \right)^{1/2}, \]

and \( \varphi \) is the electrical potential, \( n \)—the number concentration of ions, and \( \zeta — z \) potential. For \( \varphi \ll 1 \) the approximate equation is

\[ \hat{\varphi}'' + \hat{\varphi}' - \kappa^2 \hat{\varphi} = 0 \]

with the boundary conditions

\[ \hat{r} = \hat{a}, \quad \hat{\varphi} = \hat{\varphi}_0; \quad \hat{r} = 1, \quad \hat{\varphi} = 0. \]

The general solution of the equations is

\[ \hat{\varphi} = c_1 l_0 (\kappa \hat{\varphi}) + c_2 K_0 (\kappa \hat{\varphi}). \]

(b) In the case of only negative charged ions we have

\[ \frac{d^2 \varphi}{d\hat{r}^2} + \frac{1}{\hat{r}} \frac{d \varphi}{d\hat{r}} = \kappa^2 e^{\varphi}. \]

This equation should be solved numerically.

In this paper only the case of equal number of negative and positive ions is considered. This case, on the one hand, is very interesting and covers a lot of practical cases and on the other hand—it allows a more simple mathematical solution and clear understanding the physics of the phenomenon.

To simplify the problem let us consider one-dimensional plane case, which is a good approximation for a thin layer (see Fig. 4). This simple case allows best qualitative understanding the affect of small additives on the turbulent flow.

The Poisson–Boltzmann equation in the case of two kinds of charged ions is

\[ \frac{d^2 \varphi}{dx^2} = \kappa^2 \sinh(\varphi), \]

where \( \hat{x} = x l^*, \) with the characteristic length \( l^* = H — a \) half distance between two micelles, and \( \kappa = H/D. \) This parameter indicates how many times the characteristic geometrical size is larger than the layer of ions surrounding a micelle. The approximate solution of Eq. (11) for \( \varphi \ll 1 \) is

\[ \hat{\varphi} = \frac{\hat{\zeta}}{\sinh(\kappa)} \sinh[\kappa(1 - \hat{x})] \]

and the strength of the electrostatic field is calculated from Eq. (12),

\[ \frac{d \varphi}{d\hat{x}} = -\frac{\hat{\zeta} \kappa}{\sinh(\kappa)} \cosh[\kappa(1 - \hat{x})], \]

or in a dimensional form
\[ E = \frac{e^2 k_b T}{\varepsilon d_0} = \frac{\zeta \cosh(\kappa(1 - \xi))}{D \sinh(\kappa)}. \]  

To calculate the electrostatic field the value of surface potential is needed, which when the charge of the surface is known, can be calculated approximately as

\[ \varphi_0 = \zeta = \frac{\sigma D}{\varepsilon \varepsilon_0}. \]

where \( \sigma \) is the surface charge concentration. This value is used for rough estimation of the \( \zeta \) potential. The precise data should be obtained experimentally by direct measurement of \( \zeta \) potential of the surfactant micelles or polymer molecules when this theory is applied to drag reduction in polymer solutions.

**III. FORCES ACTING ON A TURBULENT FLOW IN THE VICINITY OF MICELLES**

The local turbulent flow in the vicinity of a micelle placed at point \( x_0 \), by a linear approximation, can be presented as

\[ u_i = (u_{i0}) + a_{ik} x_k, \]

where \( a_{ik} = \partial u_i / \partial x_k \) and \( (u_{i0}) = u_i(x_0, t) \) is the linear velocity of the micelle. In the coordinate system connected to a single micelle, moving with the flow, the velocity distribution is

\[ u_i = a_{ik} x_k. \]

The tensor \( a_{ik} \) can be presented as a sum of symmetric and antisymmetric parts

\[ a_{ik} = \frac{1}{2}(a_{ik} + a_{ki}) + \frac{1}{2}(a_{ik} - a_{ki}), \]

where the symmetric part presents a rigid body rotation, while the antisymmetric part is the strain flow (see Fig. 5).

In coordinate system rotating with the volume, the coordinate axes coincide with the main axes of the tensor \( a_{ik} \), and the velocity vector becomes

\[ \vec{u} = (a_{11} x_1, a_{22} x_2, a_{33} x_3). \]

The continuity equation for noncompressed liquids yields the equation for the coefficients

\[ a_{11} + a_{22} + a_{33} = 0. \]

If \( a_{11} \) is chosen as the biggest positive velocity of deformation and \( a_3 \) as the biggest negative velocity of deformation the next inequality holds:

\[ 0 < a_{11} \geq a_{22} \geq a_{33} < 0. \]

For the local energy dissipation the following expression can be deduced from the Navier–Stokes equations (see Monin and Yaglom):

\[ a_{11}^2 + a_{22}^2 + a_{33}^2 = \bar{\tau} \overline{T}/2 \nu, \]

where for turbulent flows \( \bar{\tau} \) is the energy of turbulent dissipation. The micelle is aligned in one of the main axes. In coordinates connected to the rigid body rotation the system micelle ions is submerged in the strain flow. In EDL the ions form kind of structure with strong bond connections between ions in the radial direction. These bonds are established as a result of electrical forces and diffusion acting in opposite directions. In the radial direction the electrical forces prevent the motion of ions. The strain flow carries the ions in the angular direction because the electrical force does not act in this direction. The ions concentrate somewhere downstream at a distance where the hydrodynamic and electrical forces acting on ions are equal (see Fig. 6). There are two questions arising from the consideration of interaction of micelle with turbulent flow.

(i) Is the strain part of the turbulent fluctuation able to take the ions away from the micelle, against the electrical attraction?

(ii) If not, are the friction forces exhibited by the “frozen” ions capable to reduce significantly the velocity of the turbulent fluctuation?
In the small Kolmogorov scale, the fluid motion is affected by friction and a change of the flow velocity. We assume that the change of flow velocity is caused by the action of the electric forces, neglecting the friction. The friction acts in the same direction as the electrical force; therefore we can omit the friction and underestimate the effect of the electrical force.

The Newton law applied to the whole liquid volume of a single cell is
\[ F_{el} = ma = \rho V a. \]  
(23)

The nondimensional force is defined in accordance with definitions (6):
\[ \hat{F} = F - \frac{l^*}{n_0 k_b T}. \]  
(24)

If the characteristic size of the liquid volume is \( l^* \) and the characteristic velocity \( U' \) is the fluctuating velocity, the characteristic time \( \tau \) is
\[ \tau = \frac{l^*}{U'}. \]
and
\[ a = \frac{U'}{\tau} = \frac{U'^2}{l^*}. \]

Finally we have the value of the hydrodynamic force which should be applied to liquid to stop it:
\[ F_h = \rho V a \sim \rho V \frac{U'^2}{l^*}. \]  
(25)

Now, let us estimate the electric force acting on the same liquid volume. We assume a mean electric force is applied at distance \( D/2 \) on the ions. The charge of all ions in the volume \( V \) surrounding a single micelle is
\[ Q = z e n_0 V, \]  
(26)
where \( n_0 \) is the mean concentration number of ions. The electrical force using Eq. (14) can be calculated as
\[ F_{el} = Q E(\xi) = -n_0 z e \xi \frac{V \cosh(\kappa(1 - \xi))}{D} \sinh(\kappa). \]  
(27)

If \( F_{el} > F_h \) or
\[ n_0 z e \xi \cosh(\kappa(1 - 1/2 \kappa)) \frac{D}{\sinh(\kappa)} > \rho \frac{U'^2}{l^*}, \]  
(28)
then even all turbulent momentum is applied to ions, it is not enough to move them away from a micelle. This is condition of ions to be frozen in the flow.

Now, the second question is do the ions influence the flow, i.e., if the friction force generated by ions can reduce the fluctuation velocity significantly. The friction force is
\[ F = n_0 V 6 \pi \mu r_{mol} U', \]  
(29)
where \( r_{mol} \) is a radius of a single molecule and if the condition
\[ n_0 6 \pi \mu r_{mol} > \rho \frac{U'}{l^*} \]  
holds the frozen ions can reduce significantly the fluctuation velocity in the part of the Kolmogorov scale, where this condition holds. In this area the turbulent dissipation can be neglected.

These relations for the mean values allow one to estimate the conditions when the electrical interaction between the micelle and the charged ions has an influence on the turbulent flow. Now, consider some typical examples to check if the presented model is relevant to real systems and if the electrokinetic effect is strong enough.

A. Numerical example

Consider an example, taking the values of physical constants and typical numerical data: \( e = 1.6 \times 10^{-19} \text{C}, \ e_0 = 8.85 \times 10^{-12} \text{CV}^{-1} \text{m}^{-1}, \ e = 80, \ k_b = 1.38 \times 10^{-23} \text{J/K}, \ \mu = 10^{-3} \text{kg/m s}, T = 300 \text{K}, z = 1. \) The number concentration (as in Hetsroni et al.\(^{16}\)) of surfactants and of the counterions as well is
\[ n_m = n_0 = 3 \times 10^{20} \text{mol/m}^3. \]
Assuming each micelle contains 1000 surfactant molecules, the number concentration of micelles in the solvent is
\[ n_m = 3 \times 10^{20} \text{micelles/m}^3, \]
i.e., the linear concentration is \( 0.63 \times 10^7 \) micelles/m and the mean distance between two micelles is
\[ 2R = 2H = 1.6 \times 10^{-7} \text{m} \text{ or } l^* = R = H = 0.8 \times 10^{-7} \text{m}. \]

Estimated length of surfactant molecule or radius of the micelle is \( L = 10^{-6} \) m. Now calculate the Debye length
\[ D = \left( \frac{e e_0 k_b T}{2 n_o z^2 e^2} \right)^{1/2} = 1.4 \times 10^{-8} \text{m} \]
and
\[ \kappa = \frac{H}{D} = \frac{0.8 \times 10^{-7}}{1.4 \times 10^{-8}} = 5.7. \]
The hydrodynamic parameters are chosen by consideration of a turbulent flow close to the wall. According to Klebanoff\(^{24}\) and Laufet\(^{25}\) the fluctuation velocity is less then 0.5U\(_c\). Using the numerical data from Hetsroni et al.\(^{16}\) we have
\[ U_c = 2 \text{ cm/s}, \ U' = 1 \text{ cm/s} = 10^{-2} \text{ m/s}. \]
Check the condition (28). The left-hand side is
\[ n_0 z e \xi \cosh(\kappa(1 - 1/2 \kappa)) \frac{D}{\sinh(\kappa)} = 7 \times 10^9, \]
while the right-hand side is
\[ \rho \frac{U'^2}{l^*} = 1.25 \times 10^9. \]

The left-hand side is few orders larger than the left one, which means that the electric forces are much higher than the turbulent small scale momentum, and the turbulent fluctua-
tions cannot enforce ions to leave the ions in the EDL from their location. Now, check the second condition, Eq. (30). The left side of this condition is

$$n_0 \delta \pi \mu a = 5.6 \times 10^{11} \text{ N/m}^3,$$

while the right side is

$$\frac{U'}{\rho} = 1.25 \times 10^8 \text{ N/m}^3.$$

The left side is much higher than the right side, which means that the friction of the frozen ions stop the flow in the EDL.

In the region of EDL the strain flow is stopped, which means that the coefficients $a_i$ in Eq. (16) are zero and hence the turbulent energy is zero in this area as well. The effect is so strong that even some rough assumption about the turbulence and the structure of the local flow have been done, the effect of electrokinetics definitely plays a significant role in the drag reduction.

**B. Reduction of turbulent parameters**

The conditions (28) and (30) allow only qualitatively estimation of the influence of EDL on the turbulent flow. It is because the thickness of the EDL is approximated by the parameter $D$, which gives only roughly the thickness of the layer. To obtain more precise results, the thickness of the layer, where the electrical forces are higher than the turbulent stresses should be calculated. The nondimensional electric force acting at some point $\hat{r}$ on a unit volume with charge given by Eq. (4) is

$$\hat{f}_e(\hat{r}) = \hat{n}(\hat{r})\hat{E}(\hat{r}) = -\frac{\zeta}{\sinh(\kappa)} \cosh[\kappa(1 - \hat{r})] \sinh(\hat{\phi}),$$

$$\hat{\phi} = \frac{\zeta}{\sinh(\kappa)} \sinh[\kappa(1 - \hat{\phi})].$$

(31)

The condition when the electrical force is higher than the hydrodynamic force and the flow is stopped is given by

$$\frac{n_0 \varepsilon \zeta \cosh[\kappa(1 - \hat{r})] \sinh(\hat{\phi})}{D \sinh(\kappa)} > \frac{\rho U'^2}{l^w}. \quad (32)$$

Equation (31) yields the distribution of the electric force per unit volume, acting on the ions. The second condition which compares the friction force with hydrodynamic one holds in the whole region of the single cell, and almost do not depend on the position where these forces are compared. Therefore, this condition is given by Eq. (30).

The ions in EDL are arranged in a stable structure with strong bond connections between ions in the radial direction. These bonds are established as a result of electrical forces and diffusion acting in opposite directions. If the hydrodynamic forces are of the same order as the electrical forces, the fluid fluctuation cannot enforce the ions to move with the fluid. The solution of inequality (32) yields the distance $\hat{r}$ from the micelle surface, where the electric forces are equal to hydrodynamic forces. This location divides the cell region in two parts. One part, closer to the micelle where the electrical forces are much higher than the hydrodynamic forces, and the second, outer part where the hydrodynamic forces are higher than the electrical forces. This point is not determined exactly, because the action of diffusion should be taken into account. But this approach allows one to estimate this location. In Fig. 7 the streamlines of a local flow inside of a single cell is presented. In the upper half circle the streamlines without influence of interaction of the flow with ions are depicted. In the lower half circle the streamlines of the flow, under the influence of interaction with the ions, do not penetrate the imaginary circle where the electrostatic forces acting on ions are of the same order of magnitude as the hydrodynamic forces. The flow inside this circle can be assumed to be stagnant as well as all turbulent parameters are zero. We do not consider the influence of the surrounding cells on the flow in the cell and reduction of the mean turbulent parameters is proportional to the ratio between the stagnant flow area to that of the whole single cell area.

Using the same numerical data as in the previous paragraph, the distribution of the electrical forces acting on the ions in a unit volume can be calculated and it is presented in Fig. 8. The value of the hydrodynamic force per unit volume...
for these numerical data is as in the previous paragraph
\[
\frac{\rho U^2}{l_s} = 1.25 \times 10^6 \text{ N/m}^3.
\]

The distance from the center of a single cell to the point where the electrical and hydrodynamic forces is more 0.6R, which means that in more than 40% of the volume the flow velocity is zero.

IV. CONCLUSION

The electrokinetic mechanism of the effect of drag reduction in surfactants solution was examined. Each micelle induces an electrical field and the surrounding ions are arranged in the EDL. In this layer the ions build a strongly connected structure as a result of electrical forces and diffusion. These ions interact with the local turbulent flow, reducing the flow velocity component in the radial direction. Two criteria, which allow one to obtain the conditions when the flow is significantly influenced by ions are derived. The first criterion compares the momentum of the turbulent fluctuation with electrical forces acting on the ions. This criterion allows one to obtain the main parameters of the flow and electrical interaction when the ions cannot be moved by the flow from their position in the radial direction. The second criterion compares friction between ions and flow with the fluid momentum. This criterion expresses the condition when the friction can stop the fluid motion.

A basic numerical example was considered to check the conditions. From this example it can be clearly seen that the electrical forces have a strong influence on the local turbulent flow in more than 40% of all the volume surrounding a single micelle, which means that the reduction of basic turbulent parameters should be at least of the same order.

The electrokinetic effect is not the only mechanism that causes reduction of the turbulence. This effect in some conditions can be very strong but in others may even vanish. Together with pure mechanical mechanisms, the electrokinetic effect can clarify different aspects of turbulent drag reduction in surfactant solutions. For example, shear-induced state is described by a sudden increase of viscosity at some critical shear rate and then it stays almost a constant value up to some higher value of the shear rate, when the viscosity is decreased suddenly back to a lower value. The essential mechanism is the hydrodynamic one, but the rearrangement of the charges in vicinity of a micelle contributes a supporting mechanism, which enhances the hydrodynamic one.

The present model is a preliminary one, which is based on the assumption of Newtonian fluid. This assumption is problematic for surfactant solution and it is acceptable only for very dilute solutions. Therefore, further research should be concentrated on an extension of the model to non-Newtonian liquids.