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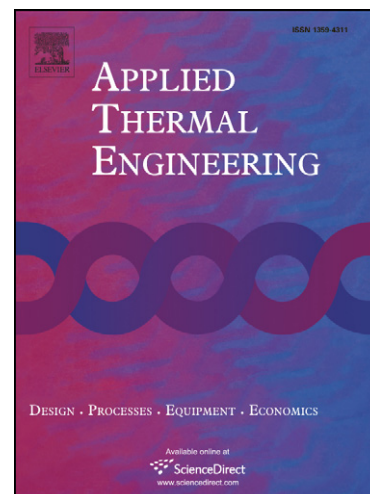
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## Drag Reducing Surfactants for District Heating

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### Abstract

An application of specific surfactants in district heating and cooling systems can give notable economical benefits due to a reduction in friction and heat transfer attributed to a formation of an additional viscous sublayer along the pipe walls, buffering the turbulence. A mathematical three-layer model of water velocity profile is composed for the calculation of drag reduction and flow-capacity increase. At a properly chosen surfactant and concentration, the local drag can be reduced up to 80%. A computer simulation and optimization for a selected district heating network model with additive shows 4% saving in total costs because smaller pipes and weaker pumps are required.

*Keywords:* Drag reduction, Surfactant, District heating, Energy saving

### 1. Introduction

The phenomenon of reduction of friction losses in turbulent flows caused by the presence of low concentrations of high-polymer additives and aluminum di-soaps has been known for almost sixty years, firstly reported by Toms [1]. Early research, focused on high-polymer

additives, was widely utilized in pipeline transport. High-polymer additives degrade under shear; therefore, further drag reduction research has shifted to surfactant additives because of their repairable nature after mechanical degradation and applicability in recirculation systems, especially in those with heat exchangers.

The drag reduction with surfactants in aqueous solutions is based on the decrease of turbulence intensity and can be explained with the formation of micelles (Fig.1). In order to minimize the unfavorable hydrocarbon-water interface, the hydrophobic molecular chains of surfactant gather together and the hydrophilic ionizable or polar heads of the surfactant form the micelles' surface. Generally, the counter-ions, such as salicylate and 3-hydroxy-2-naphthoate, additionally stabilize the interface and consequently the rod-like micelles can be formed at lower concentrations and higher temperatures.

*Fig. 1: Micellization: (a) Habon G, and (b) Ethoquad T13/50*

The detailed measurements of the velocity profile in the near-wall region has revealed that the main effect of the additives is to cause a thickening of the buffer layer - an intermediate layer between the laminar and turbulent layer [2]. This drag reduction ability at concentrations as low as a few mmol/L can be even higher than in polymer solutions. The micellization occurs when the concentration of the surfactant solution is above the threshold concentration: at the first threshold the spherical micelles are formed, and above the second threshold the rod-like micelles are favorable, acting similarly as polymer chains [3, 4]. The geometries of surfactant and counter-ion molecules play an important role in micelle formation [5]. Surfactants with smaller head-groups show better drag reduction abilities at higher temperatures. For instance, alkyltrimethylethyl ammonium bromide (with 2.5 molar ratio of salicylate to the surfactant) gives high drag reduction at temperatures from 20 to 70 °C, while

alkyldimethylethyl ammonium bromide (with the same molar ratio of salicylate, but bigger head-group) gives similar drag reduction at temperatures from 10 to 50 °C [6].

Hypothetically, they are also capable of higher net-structure formation which could explain higher steepness of the limiting curve in the elastic sublayer in comparison to the polymers [7].

In flow regions with very high value of shear stress, the micellar structures and net-structures are broken down and the drag reduction ceases. However, the degradation is reversible as surfactant molecules can regroup and repair micellar structures in a matter of seconds when the shear is reduced below the critical value, recovering drag reducing ability [8].

Generally, surfactants are grouped into classes of non-ionic, anionic, cationic and zwitterionic surfactants, depending on the electric charge of the hydrophilic part. Anionic surfactants could be highly efficient for drag reduction, but their application in real water processing systems is limited due to their deactivation by calcium and magnesium cations, which are abundantly present in terrestrial and ground waters. Quaternary ammonium surfactants ( $\text{H}_3\text{C}-(\text{CH}_2)_n-\text{N}^+-\text{R}_3$ ; R is for instance  $\text{CH}_3$  or  $\text{C}_2\text{H}_4\text{OH}$  and  $n=15$  to  $21$ ) have been proven to be the most effective drag reducers in broad temperature ranges and thus may be suitable for application in district heating and district cooling systems. Salicylate, m-chlorobenzoate and p-chlorobenzoate have been reported as the most effective counter-ions. Chlorobenzoate with para position of the hydrophobic substituent is more effective at high temperatures, and meta position is more effective at lower temperatures [9, 10]. Here are some commercial surfactants listed:

- Dobon G, produced by Hoechst Comp., AG, is a mixture of n-alkyldimethylpolyoxethyl ammonium-3-hydroxy-2-naphthoate,  $n=20-22$ , and sodium salicylat. It is efficient in temperature range from 40 to 140°C and usable up to 3 years.

- Habon G, produced by Hoechst Comp., FRG, is a mixture of 53.5% active matter in isopropanol and water. The cationic surfactant is hexadecyl-dimethyl-hydroxy-ethyl ammonium and the counter-ion is 3-hydroxy-2-naphthoate. It has excellent effectiveness at 30 to 100°C and very good durability.
- Ethoquad T13/50, produced by Akzo Nobel Chemicals Inc., is a mixture of 50% active matter in isopropanol and water. The cationic surfactant is tallow-tris-hydroxy-ethyl ammonium acetate and the counter-ion is provided with sodium salicylate (NaSal).
- Arquad 18-50, produced by Akzo Nobel Chemicals Inc., is a mixture of 50% active matter in isopropanol and water. The cationic surfactant is octadecyl-trimethyl ammonium chloride and a counter-ion is NaSal, applicable at 30 to 90°C.
- CTAC, produced by Akzo Nobel Chemicals Inc., is a mixture of 50% active matter in isopropanol and water. The cationic surfactant is cetyl-trimethyl ammonium chloride and the counter-ion is NaSal. Its effectiveness is increasing with temperature and a very good reducer at least up to 60°C.
- DR-0205 is a new product of Akzo Nobel Chemicals Inc.. It contains 30–35% of zwitterionic surfactant betaine (Rapeseedamidopropylbetain), approximately 20% butanol, C<sub>12</sub>–C<sub>14</sub> alkylether sulphate, sodium salt. Recommended temperature range is 20 to 65 C.
- SPE 98330 is also a zwitterionic surfactant, produced by Akzo Nobel Chemicals Inc.. It is a mixture of C<sub>16</sub>-betaine and Na-dodecyl-benzene sulfonate. Active content in this product is only 33%. It is very effective agent for drag reduction at low temperatures.

These surfactants show approximately the same drag reduction effectiveness, however, the Reynolds number range, where the drag reduction is manifested, differs substantially depending on the surfactant chemical structure, on its concentration and on the age of the solution. The

higher the concentration of the surfactant, the higher is its resistance to decay by age and subsequent loss of drag reduction ability.

Drag reduction effectiveness is negatively influenced by disturbances in the flow. This problem can be overcome with application of higher concentrations. Zwitterionic surfactants are easily biodegradable and are environmentally more viable than the cationic ones, but at the recommended low concentration, they are very sensitive to upstream disturbances in the flow which can spoil their effectiveness [11].

A mitigation of erosion-corrosion by drag-reducing cationic surfactants can be expected, such in the case of the oleyl-trimethyl ammonium cationic surfactant and NaSal preventing the removal of the pre-existing oxide films on copper in turbulent flow conditions, otherwise not observed, even in the tests performed with benzo-triazole, which is known as a good corrosion inhibitor for copper [12].

With old pipe networks, the system should be cleaned before using the surfactant because of the presence of tiny absorptive particles. A safe precaution against biodegradation of surfactant in a long operated heating system must be taken [13].

From an ecological point of view, the toxicity of cationic drag-reducing additives is similar to other wetting agents that lower the interfacial tension, commonly used as detergents, emulsion and foam stabilizers. In the case of leakage from the district network, the surface activity of the additive is neutralized by anions in the soil and irreversibly absorbed into the clay. The accumulation is much reduced due to high biological degradability. In the case of disposal of such water, the additives can be removed with ultrafiltration or irreversibly adsorbed on anionic neutralizer, for instance

bentonite. The fish test should be done before direct release into terrestrial waters as the surfactants can cause gill swelling.

An extensive research and test program concerning the use of additives for district heating and cooling systems has been carried out in various countries (Canada, Germany, The Netherlands, Sweden and the USA). Habon G and Dobon G have been examined in laboratory and field tests with the conclusion that there are no serious technical problems in relation to the use of these additives in district heating systems. However, but because of slight toxicity (although not more harmful than many surfactants used in industry and households) the use should be limited to primary heat transmission systems, which are hydraulically isolated from distribution networks. The greatest concern is attached to the possible leakage into the surroundings (drinking water resources) and the risk of contaminating consumers' hot sanitary water [14].

## **2. A Model for Velocity Profile with Drag Reducing Surfactants**

When inducing such surfactants for practical application, new pressure conditions accrue along the network and improved models for water flow profile are needed for computer modeling and optimization of pipe networks. For this purpose, a model for mean velocity profile in turbulent boundary layer of pipe flows with added surfactants is composed for numerical evaluation of drag reduction and flow capacity.

Virk et al. examined friction factor and velocity profile for a large number of different long-chain polymer solutions of relatively low concentrations. Their work determined the basic characteristics of the Toms phenomenon: the existence of a universal maximum drag reduction asymptote (now named after Virk), and the existence of an onset shear stress for drag reduction.



Colebrook White friction factor,  $\lambda$ , was lower than the values for pure water (Eq. 1) and the asymptote (Eq. 2) was found to be universal, independent of system and additive properties [15].

Later, a number of investigators using surfactants observed that friction factors are reduced even below the Virk's asymptote. Zakin proposed an asymptote, given by Eq. 3 [16]. Plots of Eqs. 1, 2 and 3 are straight lines in log-log scale and for given ranges of Re very close to the practical curves that are presented in Fig. 2. Actual curves for  $\lambda$  depend on surfactant species, concentration, temperature and pipe diameter and have minimums along the Zakin's asymptote.

Blasius's relationship for water:

$$\lambda = 0.3164 \text{Re}^{-0.25}; \text{Re} = 2320 \text{ to } 10^5 \quad (1)$$

Virk's asymptote for polymers:

$$\lambda = 2.32 \text{Re}^{-0.58}; \text{Re} = 4000 \text{ to } 40\,000 \quad (2)$$

Zakin's asymptote for surfactants:

$$\lambda = 1.26 \text{Re}^{-0.55}; \text{Re} = 10^4 \text{ to } 5 \cdot 10^4 \quad (3)$$

*Fig.2: Friction factor for water, and asymptotes for polymer and surfactant additives [16].*

The mechanism of drag reduction caused by polymers lies in a formation of an additional sublayer between viscous sublayer along the pipe wall and turbulent core. The presence of long chains buffers turbulence and enables steep increase of local water velocity, in direction from the wall toward the pipe axis, resulting in higher mean flow velocity.

When observing a velocity profile in pure water (see Fig. 3), there are two layers present:

- viscous sublayer at the wall:

$$u^+ = y^+; \quad y^+ < 11.6 \quad (4)$$

- turbulent core:

$$u^+ = 2.5 \ln y^+ + 5.5; \quad y^+ > 11.6 \quad (5)$$

Where the parameters are:

$$u^+ = \bar{u} / u^* = \text{dimensionless velocity, (-)}$$

$$y^+ = yu^* / \nu = \text{dimensionless distance from the wall, (-)}$$

$$u^* = \sqrt{\tau / \rho} = \text{shear velocity, (m/s)}$$

Virk [17] proposed a three-layer model for the velocity profile in water with high-polymer additives (Fig. 3):

- viscous sublayer:

$$u^+ = y^+; \quad y^+ < 11.6 \quad (4)$$

- elastic sublayer:

$$u^+ = 11.7 \ln y^+ - 17.0; \quad y^+ < y_e^+ \quad (6)$$

- turbulent core:

$$u^+ = 2.5 \ln y^+ + 5.5 + \Delta B; \quad y^+ > y_e^+ \quad (7)$$

Parameter  $\Delta B$  is parallel shift above line (5) and depends on polymer species, concentration, and Re. Parameter  $y_e^+$  is dimensionless thickness of the boundary layer.

For surfactants, Zakin et al. [16] proposed a new limiting asymptote (Eq.8, Fig. 3) and Myska [18] proposed a plug profile in the turbulent core (Eq.9, Fig. 3).

- elastic sublayer:

$$u^+ = 23.4 \ln y^+ - 65.0; \quad 15 > y^+ < y_e^+ \quad (8)$$

- turbulent core:

$$u^+ = E \quad (9)$$

Parameter  $E$  depends on surfactant species, concentration and Re.

*Fig. 3: A scheme of dimensionless velocity profiles for water, polymer and surfactant additives*

Additionally, when considering the heat loss during the warm water transportation, the presence of elastic sublayer gives an insulating effect. The heat transfer coefficients measured for surfactant solutions are even lower than those measured for polymer solutions [19, 20]. When entering in the heat exchangers at buildings' heating circuits, the desired heat transfer may be provided by temporary demicellization due to shear stresses, already existent or produced mechanically. Using the proper surfactant inside the building heating circuit, the heating efficiency of radiators is also not affected [13].

### **3. An evaluation of drag reduction and flow-capacity increase**

District-heating systems ensure savings by consumption of primary energy and ecological heat supply. From the economic point of view, there is a contradiction between low heat-generation costs and relatively high distribution costs. The investment in pipelines and pumps, together with the pumping costs, form a major cost item of the system. Additionally, district-heating systems suffer heat losses along the grid, depending on the degree of insulation of the pipelines. The average losses in Italy during the year 2000 for instance were estimated at 11% of whole thermal energy produced by the plants [21]. For these reasons the costs for such systems are favorable only at short transport distances and populous urban regions [22, 23]. When the consumers are

scattered, a better overall economy and important environmental benefits can be achieved with smaller distributed production plants instead of a large central plant [24].

An addition of small amounts of properly chosen surfactant into water can significantly reduce pumping energy losses or reduce the investment in a new pipe network as smaller pipe diameters and pumps with lower power are required.

When a particular flow velocity,  $v$ , is required; or to restore higher velocity at the same pumps' power, pressure drop is evaluated by Darcy's equation:

$$\Delta p = \frac{\rho v^2}{2} \cdot \frac{\lambda L}{D} \quad (10)$$

Parameter  $D$  is pipe diameter,  $L$  is pipe length of the particular network segment and  $\Delta p$  is pressure loss along the pipe in this segment.

Considering the water velocity as constant, maximal drag reduction,  $DR_{\max}$ , can be predicted by expressing  $\Delta p$  with Darcy's equation (10), and substituting  $\lambda$  with Blasius's equation (1) for water, and  $\lambda$  for additives with the asymptote (2) or (3):

$$DR = \frac{\Delta p_{\text{water}} - \Delta p_{\text{additive}}}{\Delta p_{\text{additive}}} = 1 - \frac{\lambda_{\text{additive}}}{\lambda_{\text{water}}} \quad (11)$$

In the range of  $Re$  from  $10^4$  to  $4 \cdot 10^4$ , for polymers  $DR_{\max} \approx 1 - 7/Re^{0.33}$  is 66.5% up to 79%, and for surfactants  $DR_{\max} \approx 1 - 4/Re^{0.3}$  is 75% up to 83%. These values can be achieved by proper selection of additive species and concentration for particular pipe diameter and  $Re$  range.

Ethoquad T13/50 (5 mmol/L) + NaSal (12.5 mmol/L), for instance, at temperatures from  $30^0$  up to  $60^0$ C, in  $Re$  range from  $5 \cdot 10^4$  to  $10^5$ , gives the maximums above 60% [25].

Considering pumps with constant power, if we have laboratory turbulence measurements for a particular surfactant that is planned to be dosed into the network, an increase in flow capacity can be evaluated. For instance, the turbulence measurements for Habon G at different concentrations

and  $Re$  are given in [26], and for Ethoquad T13/50 in [18]. Here, the determination is made for Ethoquad T13/50 from Fig. 4.

Fig. 4: Dimensionless velocity profile for Habon G (2mmol/L) and Ethoquad T13/50 (2 mmol/L) + NaSal (6.25 mmol/L), in a pipe with diameter 39.4 mm [18]

Water flow capacity through a pipe is:

$$q_v = 2\pi \int_0^{D/2} \bar{u} \left( \frac{D}{2} - y \right) dy = \pi D v \cdot \Delta I \quad (12)$$

$$\Delta I = \left( \int_0^{Re^*} u^+ dy^+ - \frac{1}{Re^*} \int_0^{Re^*} u^+ y^+ dy^+ \right) \quad (12a)$$

$$Re^* = y_{(y=D/2)}^+ = \sqrt{\frac{\tau}{\rho}} \cdot \frac{D}{2\nu} \quad (13)$$

$$FI = \frac{q_{additive}}{q_{water}} - 1 \approx \frac{\Delta I_{additive}}{\Delta I_{water}} - 1 \quad (14)$$

$Re^*$  is  $y^+$  at the pipe axis (the last measurement point in Fig.4). It can be also calculated by (13), when  $\tau$  vs.  $v$  is known. For Ethoquad, calculating  $v \approx 2.4$  m/s from  $Re=93200$  and finding

$\log \tau \approx 0.4 + 1.3 \log v$  in the range of  $v$  from 0.5 to 5 m/s [26],  $Re^*$  is 1500.

Flow-capacity increase (Eq. 14) can be estimated by a computer calculation of integrals (12a) from measurement data  $u^+(y^+)$  for a chosen additive. In our case, Ethoquad T13/50 can give 2.5-times higher flow capacity than in the case of pure water.

For the cases that only a few measurement points  $u^+(y^+)$  are available for a particular surfactant and flow conditions, a model for velocity profile [27], developed on bases of Prandtl's mixing-length theory, can be used:

$$u^+ = \int_0^{y^+} \frac{1 - \frac{y^+}{\text{Re}^*}}{m + \alpha(y^+)^p} dy^+ \quad (15)$$

Parameter  $p$  is between 2 and 3. Surfactant gives lower  $p$  by reducing the mixing length, which means a steeper elastic-layer line in semi-log scale. Parameter  $\alpha$  is determined by the velocity in turbulent core and strongly depends on  $\text{Re}$ . the higher the velocity, the higher  $\alpha$  will be.

The parallel shift of the elastic-layer line is signified by  $m$ . It can be taken as constant for a chosen surfactant specie and concentration. These parameters have been determined by a numerical simulation of the integral (15) for Ethoquad T13/50 and Habon G (from Fig. 4) as representative surfactants. Results are given in table 1.

*Tab. 1: Values of numerically determined parameters in (15) for the cases from Fig. 4.*

For economic estimation, in a real district heating network in an urban area (16 net nodes and 10 local heating stations, input pressure 1MPa in central station, 42 well-insulated pipe sections with total length 10 km and total flow requirement 165 m<sup>3</sup>/h), a section (18 paths with total length 3.6 km) was selected, numerically simulated and optimal net was searched considering all investment and operating costs (Fig. 5). The computation was done with the iterative simplex method described for the similar study case (without additives) in [22]. The construction (land and building) costs were evaluated with 10% annual discount rate. The life time for pipelines was predicted 40 years and 10 years for

pumps. Pumping costs were evaluated at 8,760 operational hours per year with 65% pump efficiency. As the input temperature was 130 °C and the reflux temperature 70 °C, the simulation was done for Dobon G (with commercial price 12.5 €/kg and diluted in water to 1.5g/L).

At resulted DR = 35% and FI = 40% in average per pipe, smaller pipes and weaker pumps are required yielding lower investment (15.7% for pipes and 25.7% for pumps), and 31.8% lower operating costs. Total saving is 10500 €/km. As the construction costs have the highest shear (around 80% for the selected section with total costs 0.95 Mio€), the savings are 4% of total costs in comparison to the case without the additive.

*Fig. 5: A principle of cost reduction at minimized pipes and surfactant application*

## 5. Conclusion

Nowadays wide interest for energy savings leads us to renewing technological and scientific expertise also in the field of heating and water transport techniques. The district heating pipelines often distribute the heat to large built-up areas, and due to transporting it over long distances, unavoidably results in high losses in both heat and pressure. These losses can be remarkably reduced by application of specific long-chain additives due to their buffering effect on the turbulence of water flow. The applicability of high-polymers in circulation systems is limited as they reduce the heat transfer in heat exchangers and on long term degrade under high-shear flow. On the contrary, the rod-like micelles of surfactants degrade only temporarily. This degradation in heat exchangers provides efficient heat transfer.

For the application of such additives in heating and cooling networks, the mathematical model for determination of fluid flow characteristics was composed for computer evaluation and simulation of pipe networks and pumps. The numerical evaluation for one study case with surfactant showed the possibility of local drag reduction up to 80%, while in the whole optimized network, smaller pipes and weaker pumps gave 4% savings in total (investment and operating) costs in comparison to the case without the surfactant.

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## Nomenclature

$D$	=	pipe diameter, m
$DR$	=	drag reduction, %
$\Delta B$	=	$u^+$ increase due to polymer additive
$\Delta I$	=	integral, defined by Eq.12a
$\Delta p$	=	pressure drop, Pa
$FI$	=	flow-capacity increase, %
$L$	=	pipe length, m
$m$	=	the parameter in Eq. 21
$p$	=	the parameter in Eq. 21
$q_v$	=	water flow capacity, m <sup>3</sup> /s
$q_{additive}$	=	flow capacity in the pipeline with added surfactant, m <sup>3</sup> /s
$q_{water}$	=	flow capacity in the pipeline without surfactants, m <sup>3</sup> /s
$Re$	=	Reynolds factor for pipe
$Re^*$	=	dimensionless distance in the pipe center
$u^+$	=	dimensionless velocity
$u^*$	=	shear velocity, m/s
$\bar{u}$	=	time-averaged local velocity, m/s
$v$	=	flow velocity, m/s
$y$	=	distance from the wall, m
$y^+$	=	dimensionless distance from the wall
$y_e^+$	=	dimensionless thickness of the boundary layer
$\alpha$	=	the parameter in Eq. 21
$\lambda$	=	Colebrook White friction factor
$\nu$	=	kinematical viscosity of fluid, m <sup>2</sup> /s

$\rho$  = mass density, kg/m<sup>3</sup>

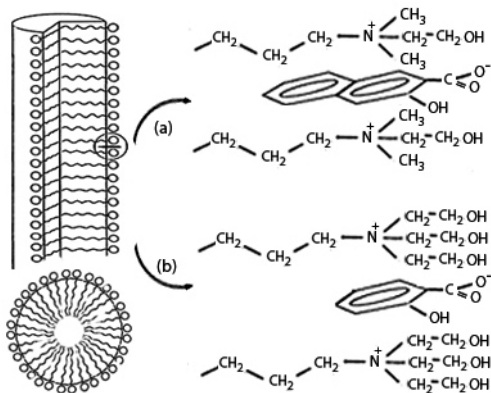
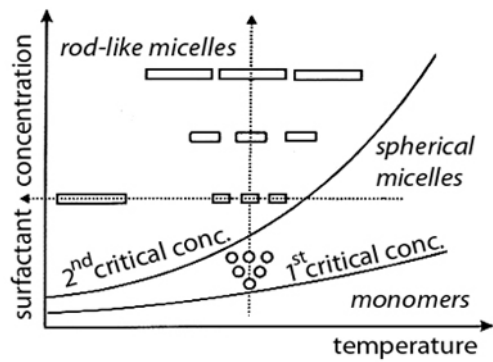
$\tau$  = shear stress, N/m<sup>2</sup>

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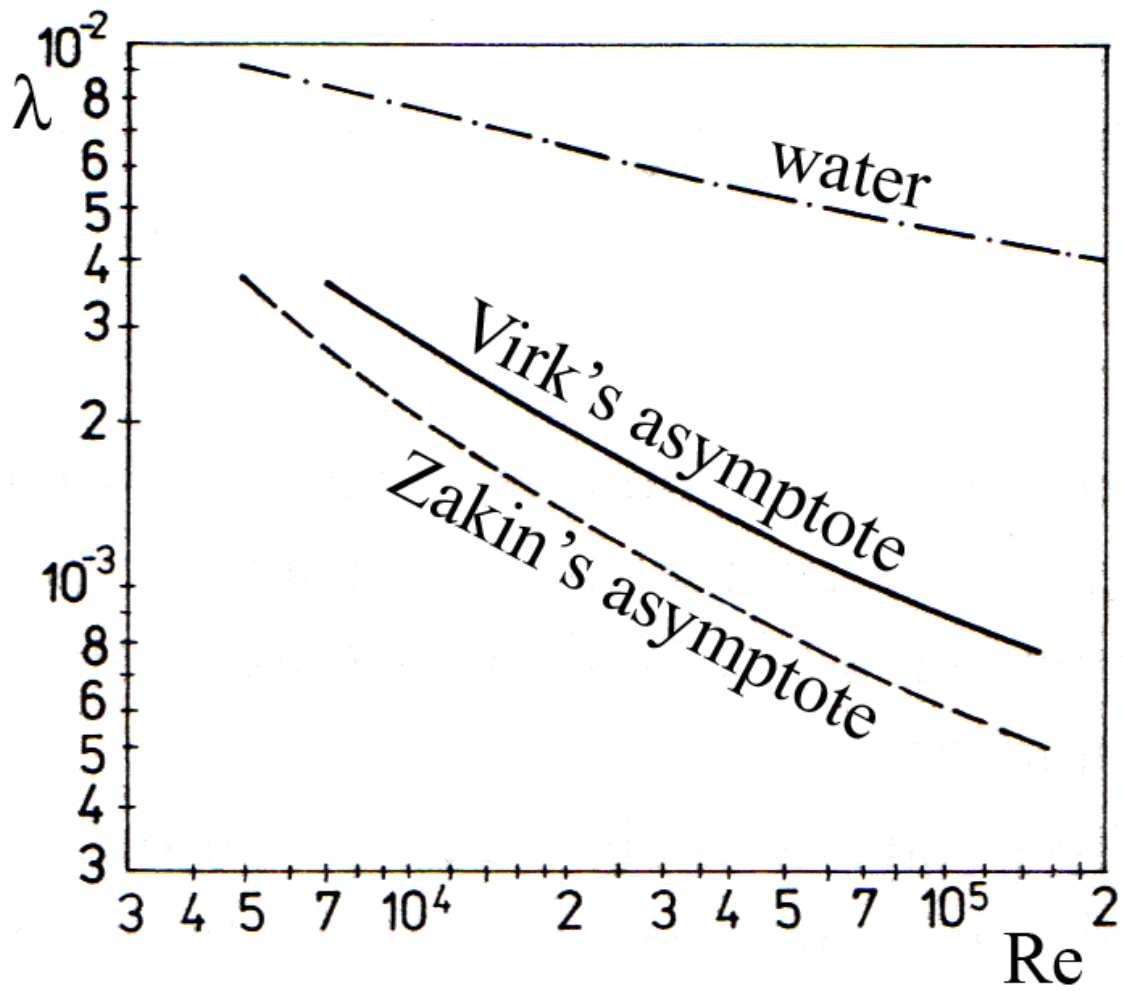
Tab.1

surfactant	$p$	$m$	$\alpha$
Ethoquad T13/50			
Re = 93200	2.6	3.5	$0.8 \cdot 10^{-5}$
Habon G			
Re = 76620	2.6	1.7	$1.6 \cdot 10^{-5}$

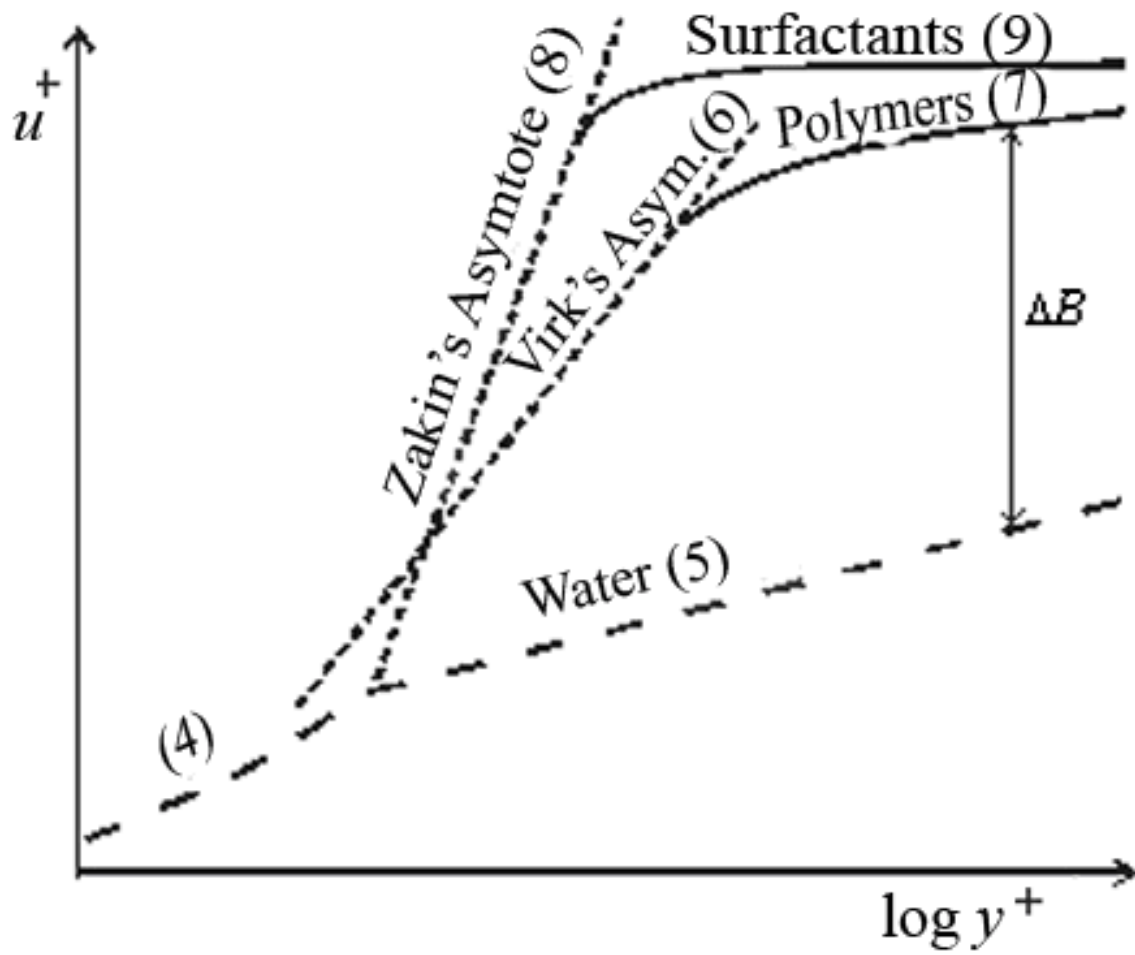
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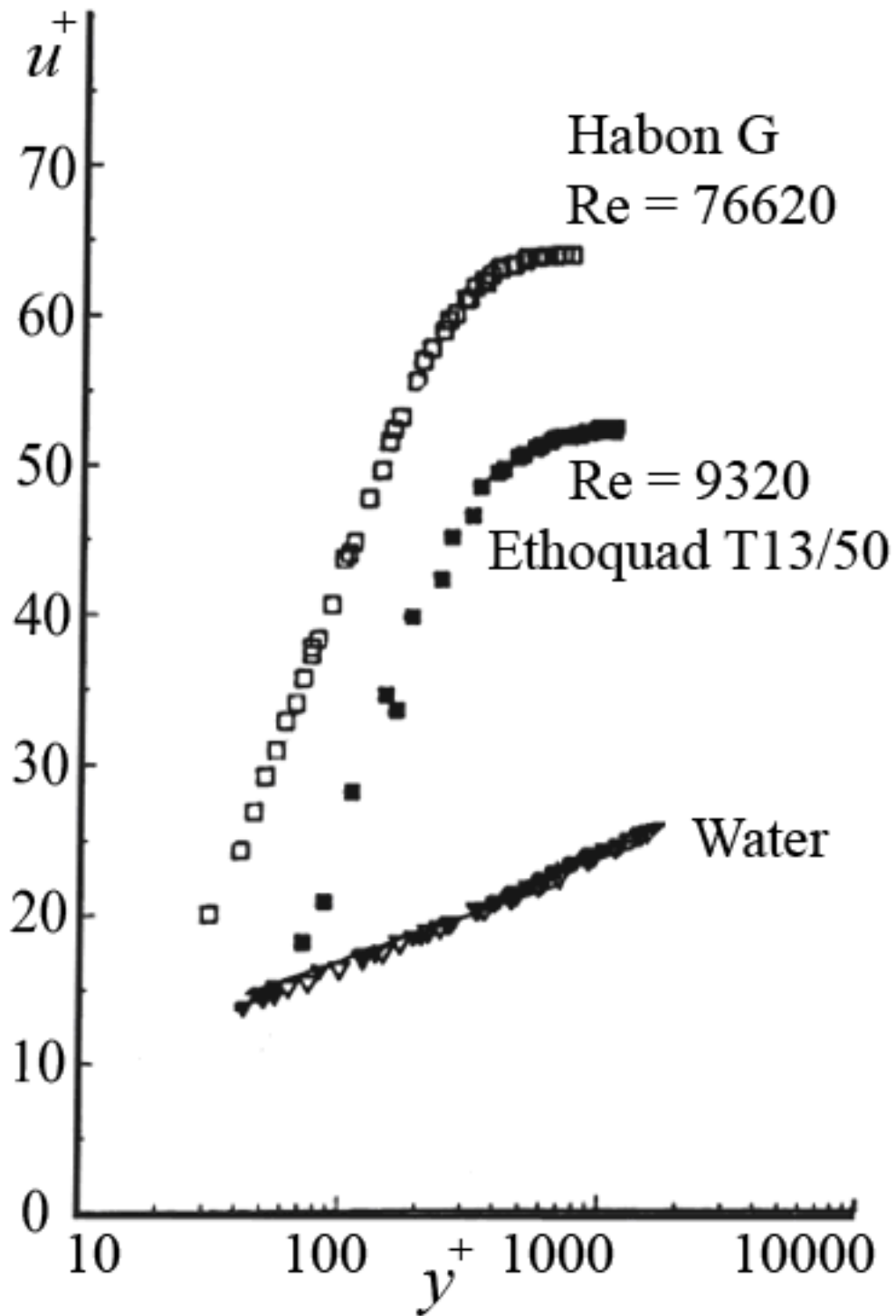


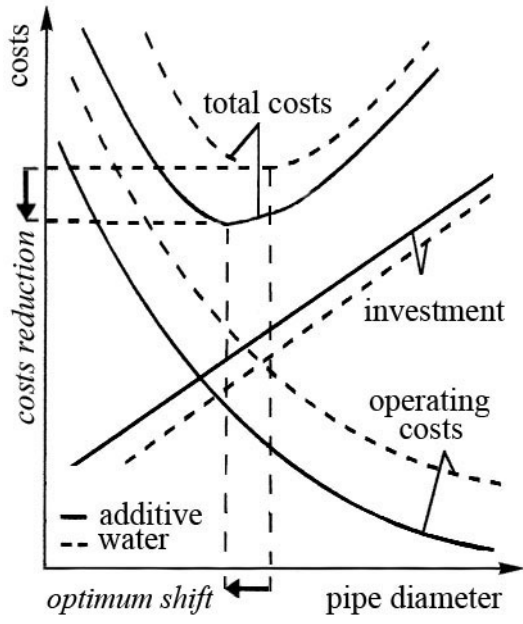
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