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ZBIGNIEW MATRAS, BARTOSZ KOPICZAK[*]

THE POLYMER-MICELLAR AGGREGATES AS AN EFFICIENT REDUCER OF THE ENERGY LOSSES IN PIPE FLOW

AGREGATY POLIMEROWO-MICELARNE JAKO EFEKTYWNY REDUKTOR STRAT ENERGETYCZNYCH W PRZEPŁYWACH RUROWYCH

Abstract

The paper presents polymer-micellar aggregates as efficient drag reducers of the energy losses in straight pipe flow. A small amount of high molecular polymers: Polyethylene Oxide, Cetyltrimetyl Ammonium Bromide surfactant and Sodium Salicylate salt additives, are applied to obtain polymer-micellar aggregates formation. An analysis of how polymer-micellar additives influence the shape and character of flow resistance curves has been performed. It is documented that for polymer-micellar solutions the stable transitional zone between, the laminar and the turbulent flows are **extended** toward higher values of the Reynolds number. Occurrence of the third turbulent zone of drag reduction is also observed.

Keywords: Energy losses, pipe flow, flow laminarisation, aggregate

Streszczenie

W artykule przedstawiono agregaty polimerowo-micelarne jako efektywny reduktor strat energetycznych w przepływach rurowych. Do procesu formowania agregatów wykorzystano niewielkie ilości wielkocząsteczkowego politlenku etylenu i substancji powierzchniowo czynnej bromku heksadecylotrójmetyloamoniowego z dodatkiem salicylanu sodu. Dokonano analizy wpływu roztworu polimerowo-micelarnego na kształt i charakter krzywych oporów przepływu. Dla analizowanych roztworów zaobserwowano rozszerzenie stabilnej strefy przejściowej w kierunku większych wartości liczby Reynoldsa. Zaobserwowano również trzecią, turbulentną strefę redukcji oporów przepływu.

Słowa kluczowe: Straty energetyczne, przepływ rurowy, laminaryzacja przepływu, agregat

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[*] Prof. PhD. DSc. Eng. Zbigniew Matras, MSc. Eng. Bartosz Kopiczak, Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Cracow University of Technology.

1. Introduction

Drag reducers have been widely investigated for more than 60 years, since the first observations of drag reduction in turbulent flows was documented by Toms [1] and Mysels [2]. Since then, the abnormal flow drag reduction by surfactant or polymer additives has been intensively examined and described in the subject literature [3, 4, 5, 6, 7, 8]. This phenomenon allows for a significant increase of the flow rate without increasing power demand, or vice versa – to reduce power demand, while maintaining a constant flow rate. It provides large potential possibilities for the application of this effect in different industry branches, particularly in the oil industry [7, 9] or in heating [8], firefighting [10], transport of slurries [7], sludge and brines [8, 11]. Causes of the described drag reduction have been perceived in the existence of a new internal solution structure, which is formulated at the moment when the special additives are introduced into the solution. Addition of high molecular weight polymer agents into the solvent results in macromolecule formation, which has a crucial influence on turbulence structure in the flow [4, 7, 12, 13,]). Although, there is still strong debate on whether a single polymer molecule or clusters of polymer molecules are responsible for the drag reduction effect, experimental results clearly prove that even a dozen of the ppm polymer concentration in solvent induces an efficient drag reduction effect in turbulent range of flow [7, 8, 14].

In case of application of surfactants as drag reducing additives, formation of micelle structures is observed [8, 12]. In order to improve the micellarisation process effectiveness in a surfactant solution, small amounts of electrolytes are applied (e.g. sodium salicylate or sodium bromide). At no motion condition, the mentioned structures are chaotic. Only during fluid flow shearing do both macromolecules and micelles start to arrange in a characteristic orientation, in accordance with the principle of minimum resistance. In both surfactant and polymer induced experiments on the drag reduction effect, a hypothetical mechanism of the phenomenon is widely accepted to be found in the interaction between polymer or surfactant molecules with the flow turbulence structure. On the basis of advanced measurement techniques, such as Particle Image Velocimetry (PIV), it is observed that the analysed polymer additives can lead to reduction or elimination of the ejections of low-momentum fluid from the wall region to the outer velocity region [14]. It is also observed that the presence of polymers leads to a decrease in the frequency and the intensity of large-scale ejections when compared to a Newtonian solvent and to the reduction of the magnitude and frequency of the small-scale eddies [15]. Usually, elongational viscosity or elasticity of polymer chain [5, 7] are proposed to explain hypothetical polymer drag reduction mechanics. On the other hand, for a surfactant aqueous solution, which reveals neither viscoelastic properties nor presence of elongational viscosity is observed [8, 13], a local shear-thickening hypothesis is proposed [8, 16].

The novel and poorly recognised effect is a phenomenon of fluid flow drag reduction by the simultaneous addition into the solvent of both high molecular polymer and surfactant with salt. In the published works related to this subject [17, 18, 19], the internal structure formation and chemical reaction process in polymer-micellar solutions are mainly highlighted. First attempts at experimental examination of turbulent wall shear stress and drag reduction effect have been performed [20, 21, 22, 23, 24, 25]. The results confirmed that simultaneous addition into the solvent of the analysed additives combines and intensifies positive features of their purely polymer and micellar analogues, providing additional extension of drag reduction zones. Moreover, the researchers indicate that this new effect requires a comprehensive experimental study to gain a deeper knowledge of this phenomenon.

Presence of polymer macromolecules in the surfactant solution enhances micelles structures formation ability. It leads to the formation of micellar structure at a lower concentration. The newly formed macromolecules are called aggregates [21, 24]. Adding a slight amount of salt (e.g. NaCl or NaSal) to the high molecular polymer and surfactant solution causes micelles size growth. The number of micelles linked with polymer chains also increases. Furthermore, the addition of the salt can increase the solution viscosity.

The aim of this paper is to perform an analysis of the drag reduction efficiency by simultaneous addition to the solvent both surfactants and high molecular polymer, comparing to the drag reduction effect obtained by addition of pure polymer or pure surfactant agents. The paper presents polymer-micellar aggregates as efficient drag reducers of the energy losses in straight pipe flow

2. Characteristic of polymer-micellar solution aggregates structure

A simultaneous addition of small amounts of polymer and surfactant additives to the solvent triggers an initiation of the micellarisation process at much a lower concentration, comparing to the critical micelle concentration (CMC) [8, 25, 27]. This concentration at which micelles formation initiation occurs in the presence of polymer macromolecules is called the critical aggregation concentration (CAC). Most of experimental studies have shown that a simultaneous addition of small amounts of polymer and surfactant agents to the solvent cause initiation of the micellarisation process at lower concentration, compared to CMC [18, 21]. The newly formed polymer-micelle macromolecules are called aggregates [21, 26, 27]. Upon the experimental study of polymer-micellar aqueous solutions [21, 24, 26], the mechanism of aggregates formation process can be described. Initially, polymer and surfactants molecules occur in the solution independently. The situation significantly changes when a small amount of salt is introduced into the solution. According to the [17, 18, 21, 27], as a result of electrostatic or hydrophobic interaction, the micelles are combined with the polymer chains by coiling around them. The final state of the mixture has single threadlike micelles with a part of polymer macromolecule chain coiled around rigid micelles, forming aggregates.

Consequently, it increases the solution's viscosity values. It should be pointed out that salt additive causes a significant viscosity decrease. It is justified by the more intensive interaction between polymer chains.

3. Material and measurments set-up

Having analysed the level of difficulty of the planned experimental tests and taking into account the type of physical quantities to be measured, the experiment was performed using a modern capillary-pipe rheometer, designed and constructed in the Division of Fluid Mechanics laboratory at the Cracow University of Technology [28]. The device allows the operator to conduct a comprehensive identification of rheological characteristics of the examined liquid in laboratory conditions.

The versatility of the described capillary-pipe rheometer allows the operator to assign not only classical experimental flow curves in the laminar range of flow, but also to examine and interpret properly the flow characteristics of fluids, which behave differently when compared with purely viscous non-Newtonian fluids in the turbulent flow region. This applies primarily to the solutions of polymers and surfactants, which are the subject of research in this work, as well as to the fluids, which can be considered on the border between the physical continuum and multi-phase system, e.g. rheostable (purely viscous) or viscoelastic suspensions. A schematic diagram of the capillary-pipe rheometer is illustrated in Figure 1.

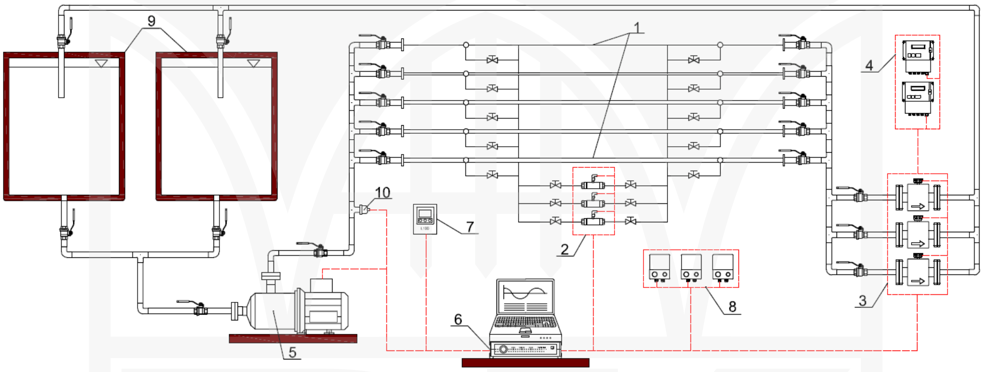

Fig. 1. Diagram of the multifunction capillary-pipe rheometer:
1 – straight capillaries and pipes with circular cross-section; 2 – differential pressure drop sensors PD1 and PDF, 3 – electromagnetic flowmeters; 4 – flowmeter controllers; 5 – Multistage rotodynamic pumps with triple-phase electrical engine; 6 – data acquisition system; 7 – microprocessor frequency converter L100; 8 – amplifiers WP-01A; 9 – tanks; 10 – temperature sensors PT 100

The basic elements of the device are straight copper and stainless steel capillaries and pipes with a circular cross-section (1). They are used for the measurement of fluid flow pressure loss at pipe distance L. Static pressure holes were spotted at distances $L_{inl} = L_{out} \approx 150d$ from the pipe inlet and outlet. This ensures stable flow conditions and eliminates the influence of the so-called "entrance effect."

The fluid flow in the capillary-pipe rheometer is forced by hermetic multistage rotodynamic pumps (5), which suck in the fluid from one of the tanks (9) and then pump it into one of the eight horizontal pipes of different diameters (1). After passing through the electromagnetic flowmeters (3), the fluid returns to the storage tank. The measurements of the pressure losses were performed using PD1 or PDF differential pressure drop sensors (2).

For the current temperature control (possibility of maintaining a constant temperature in the measuring system was provided), a resistive temperature sensor (10) was placed in the fluid supply pipe.

Pumps can work in either series or parallel arrangements, depending on the required flow rate or pressure loss value. This allows the operator to obtain a wide range of Reynolds number reaching the value of 3×10^5 for the measurement system pressure value up to 10 bar, without the loss of fluid continuity (no foaming of the solution or air bubbles).

A microprocessor frequency converter (7) was used to control the pump frequency and consequently the volumetric flow rate. The main element supporting the action of the capillary-pipe rheometer is a multi-channel data acquisition system SPIDER 8 (Hottinger Baldwin Messtechnik), arranged to measure the electrical signals from the different sensors (tension, force, pressure, displacement, acceleration and temperature sensors).

Additionally, large volume tanks (1 m^3) were used to eliminate the effect of foaming of micellar and polymer-micellar solutions and to minimise the influence of the unavoidable degradation of the polymer-micellar aggregates or macromolecular structures on measurement results.

During the preparation of the polymer-surfactant solutions, pH of the chosen drag reducing additives should be particularly considered. Incorrect selection of pH may result in an undesired chemical reaction.

Anionic surfactants cannot be used, while aqueous solutions of certain polymers can have an acidic reaction. Cationic and anionic surfactants can be combined with non-ionic polymer solutions.

After the preliminary study, the following drag reducers have been used for the experimental analysis:

- Poly(ethylene oxide) $[CH_2\ CH_2\ O]_n$ (PEO) – non-ionic polymer with viscosity-based high molecular weight given by the manufacturer equal to $8\cdot10^6$ g/mol^{-1}, purchased from Sigma-Aldrich, Inc.
- Cetyltrimetyl ammonium bromide $[CH_3(CH_2)i_5N(CH_3)_3]+Br\sim$ (CTAB) – cationic surfactant purchased from Sigma-Aldrich, Inc.

In order to lower the CAC value, salt $C_7H_5NaO_3$ (NaSal) sodium salicylate has been used. Different compositions of polymer, surfactant and salt mass fraction in solvent were used in order to analyse the chemical additive concentration effect. Distilled water was used as a solvent. Polna, Inc. Electrical Distillatory Type DE20 was used to purify tap water. The conductivity of the solvent was of the order of 1µS/cm.

After the addition of the appropriate drag reducers to the solvent, the solutions were mixed gently so as not to cause mechanical degradation of polymer chains. The first mixing was performed in cylindrical vessels, by the use of our own designed roller mixer with very a low rotational speed equal to 1÷5 rpm. Then, the solution was diluted in the main tanks. Before measurements, the mixtures were left to rest for 24 hours.

Adiabatic steady flow of homogenous solutions was examined in 8 different straight pipes with diameters between 1.8mm and 21mm, all with a temperature of 27˚C.

4. Rheological characteristics and flow resistance measurements results

In order to identify the rheological characteristics of the analysed solutions, each of the experimental/pipe flow curves have been drawn in form of functional relationship described by the Equation (1):

$$\tau_w = f(\Gamma) \tag{1}$$

where: $\tau_w = \dfrac{D\Delta P}{4L}$ – shear stress on pipe wall,

$\Gamma = \dfrac{8v_m}{D}$ – pipe shear rate (value of shear rate on pipe wall).

An interpretation of experimental results presented in form of function (1) indicates that the analysed solutions can be successfully approximated with the Ostwald de Waele power-law fluid model. Representative rheological characteristics in form of experimental/pipe flow curves are illustrated in Figure 2.

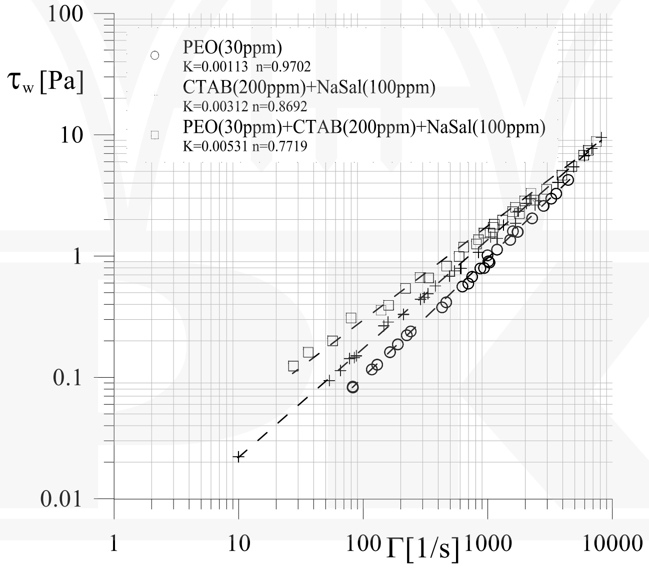

Fig. 2. Representative experimental flow curves for polymer, surfactant and polymer-surfactant solutions

Additionally, representative diagram of the shear viscosity curves vs. shear rate for the analysed solutions, which correspond to Figure 2, are presented in Figure 3.

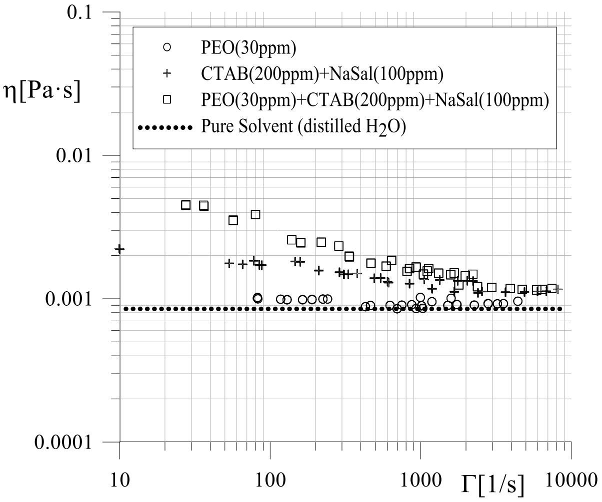

Fig. 3. Representative shear viscosity curves as a function of shear rate for polymer, surfactant and polymer-surfactant solutions

The mass fraction of individual additives, composing rheologically complex polymer-micellar solution, affects the value of the n flow index. This parameter characterises non-Newtonian properties of a fluid. There is no way to predict a priori, its value for a solution composed is arbitrarily and having different mass frictions of particular drag reducers. It was only observed that the increase of both CTAB and NaSal concentration in the examined solution having a constant polymer concentration leads to the intensification of non-Newtonian properties of the fluid, i.e. to the increase of the value of fluid consistency constant K and the decrease of the n flow index.

The interpretation of experimental data and the assessment of the respective solution additives' influence on the increase or reduction of the flow resistance and the shape and location of resistance curves depend significantly on the adopted coordinate system in which these data is presented. Firstly, experimental results of flow resistance are presented in the classical system of dimensionless numbers [Re_s, c_f] described by formulas (2) and (3):

$$Re_S = \frac{v_m \cdot \rho_S \cdot d}{\eta_S} \tag{2}$$

$$c_f = \frac{d \cdot D \cdot P}{2 \cdot r \cdot \mathrm{v}_m^{\ 2} \cdot L} \tag{3}$$

and additionally, in the form of drag reduction coefficient *DR*, defined as a function of the Reynolds number (2), and described in percentage term:

$$DR = \left(1 - \frac{c_f}{c_{fS}}\right) \cdot 100\% \tag{4}$$

Figure 4 presents the flow resistance curves of polymer, surfactant and polymer-surfactant water solutions, defined in the system of dimensionless numbers (2) and (3).

Analyses of flow resistance curves reveal that in any of analysed flow ranges measurement points do not correspond to the theoretical functions, which describe Newtonian fluid flow. The simultaneous addition of even small amounts of high molecular polymers and surfactants causes an increase of flow resistance in the laminar range of flow.

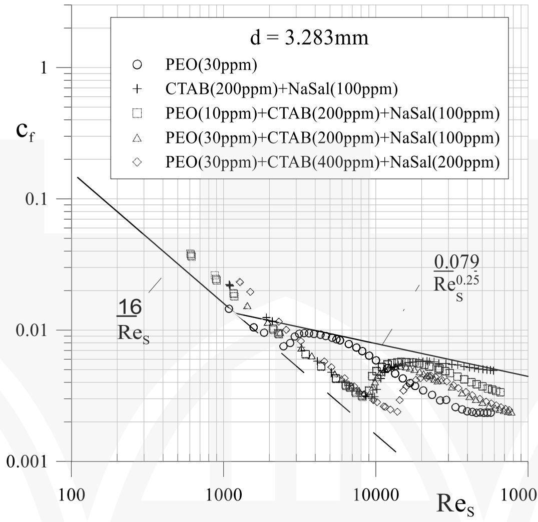

Fig. 4. The flow resistance curves of polymer, surfactant and polymer-micellar water solutions, defined in the system of dimensionless numbers (2) and (3)

The drag reduction coefficient curves (4) are illustrated in Figure 5. It is observed that in case of the turbulent flow simultaneous application of analysed chemical additives produces the drag reduction effect.

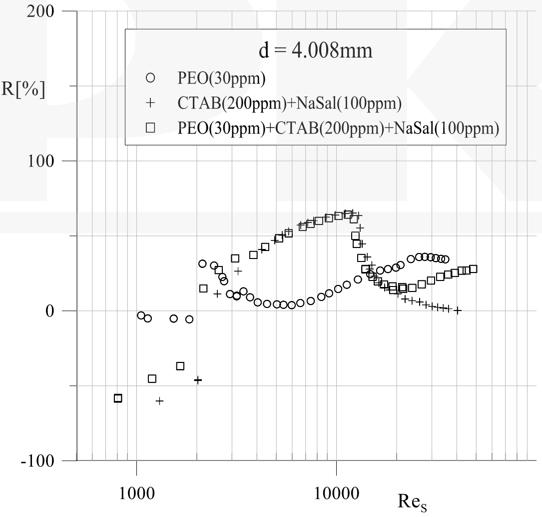

Fig. 5. The drag reduction coefficient curves *DR* = *f*(*Re*)

Due to the difficulty in unambiguous determination of the critical value the Reynolds number Re_s, the *DR* values presented in Figure 5 are calculated in such a way that it was assumed that $c_{fs} = 16/Re_s$ in the range of the Reynolds number $Re_s < 2100$, whereas the formula $c_{fs} = 0.079/Re_s^{-0.25}$ was used in the range of Reynolds number $Re_s \geq 2100$. Therefore, a sharp increase of the DR value observed in the transition zone, particularly in the polymer solution (see in Figure 5), does not reflect the actual degree of drag reduction in this range of flow. In case of the polymer solution flow, in the initial stage of the turbulent flow, no noticeable reduction of flow resistance is observed. Only after exceeding certain characteristic Reynolds number $Re_s \approx 1.5 \cdot 10^4$, the onset of the drag reduction effect occurs and the phenomenon increases with the increase in the value of the Reynolds number. A similar increase in the reduction of the shear resistance in rotating disc apparatus for the turbulent flow range, induced with PEO additive, was observed in the drag reduction effect obtained by the use of a rotating-disk apparatus [22].

Furthermore, the value of the critical Reynolds number, for which transition from the laminar flow to the turbulent flow is observed, takes various values, which depend on pipes' diameters, type and concentration of chemical additives introduced to the solvent.

A better interpretation of the simultaneous addition of the polymer and surfactant with salt effect on drag reduction, in comparison with adequate addition of pure polymer or pure surfactant with salt, can be achieved by presentation of the same measurement date in modified system of "pseudorheostable" numbers [Re_M, c_{fM}]. The modified system on dimensionless numbers used in the analysis is described correspondingly by formulas (5) and (6):

$$Re_M = \frac{d^n \cdot v_m^{2-n} \cdot \rho_S}{K \cdot \left(\frac{3 \cdot n + 1}{4 \cdot n}\right) 8^{n-1}} \cdot \left[\frac{2 \cdot (n+1)}{3 \cdot n + 1}\right]^{-2,5} \tag{5}$$

$$c_{fM} = \frac{d \cdot \Delta P}{2 \cdot \rho_S \cdot v_m^2 \cdot L} \cdot \left[\frac{2 \cdot (n+1)}{3 \cdot n + 1}\right]^{2,5} \tag{6}$$

As one knows [5], in such defined dimensionless numbers system flow resistance curves of rheostable (purely viscous) non-Newtonian fluids are transformed to a single curve – in the whole range of modified Reynolds numbers (5) – identical to the classical Newtonian curve described in the laminar range by Fanning equation and in the turbulent flow by Blasius formula. Selection of such a coordinate system was dictated additionally by the fact that it facilitates identification and description of the characteristic drag reduction flow zones. In this modified system of pseudorheostable dimensionless numbers [Re_M, c_{fM}], each deviation of experimental flow resistance curve, which indicates abnormal drag reduction from pseudorheostable Blasius curve, allows for the identification of the influence of specific additives (polymers or/and surfactants with salt) on the range of analysed drag reduction effect. Figure 6 presents comparison of flow resistance curves in the modified dimensionless number system (5) and (6) for 3 types of solutions with different internal structures.

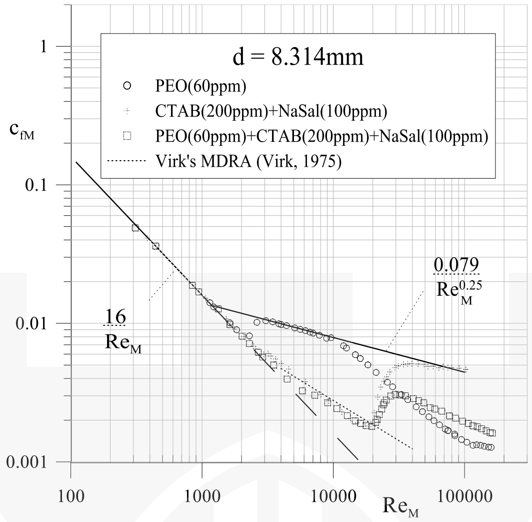

Fig. 6. The flow resistance curves of polymer, surfactant and polymer-surfactant water solutions, defined in the system of cardinal numbers (5) and (6).

The results of experimental data analysis indicate that polymer-surfactant-salt additives cause significant drag reduction in a wider range of flow in comparison with pure polymer or pure surfactant-salt solutions. Surfactant and salt additives (micellar solution) induce appearance of the stable transitional zone B (compare Figure 6 and Figure7), in which spectacular reduction of flow resistance is observed – usually greater when compared to the same effect achieved with polymer additives.

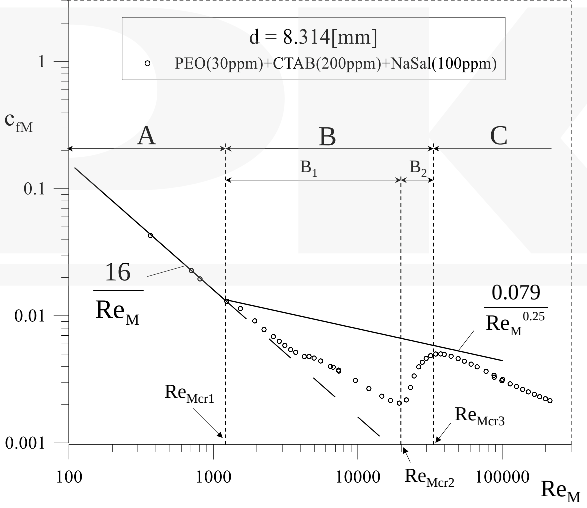

Fig. 7. The scheme of characteristic flow resistance curve zones for representative polymer-micellar solution: A – laminar zone, B – extended transitional zone (B_1 – stable transitional zone, B_2 – unstable transitional zone), C – turbulent zone.

It is observed that in the stable transitional zone B_1, the loss of the stability of the laminar flow increases very softly when the Reynolds number values grow. In this range, relative drag reduction is the greatest. Beyond a certain second critical value of the Reynolds number Re_{Mcr2} the occurrence of an unstable transitional zone B_2 is observed. It is especially well-illustrated in Figure 7. In this range of flow, a rapid loss of drag reduction effect occurs.

From Figure 6, it is documented that for polymer-micellar solutions, beyond a certain third critical value of the Reynolds number Re_{Mcr3}, the fluid starts to behave like a classical rheostable non-Newtonian fluid.

However, in comparison with pure micellar solution, an additional abnormal drag reduction zone C (see Figure 7) in the turbulent range of flow is observed in case of analysed polymer-micellar solution. The viscoelastic properties of the solution are a dominant factor in this zone of flow. This effect is also well-illustrated in Figure 8.

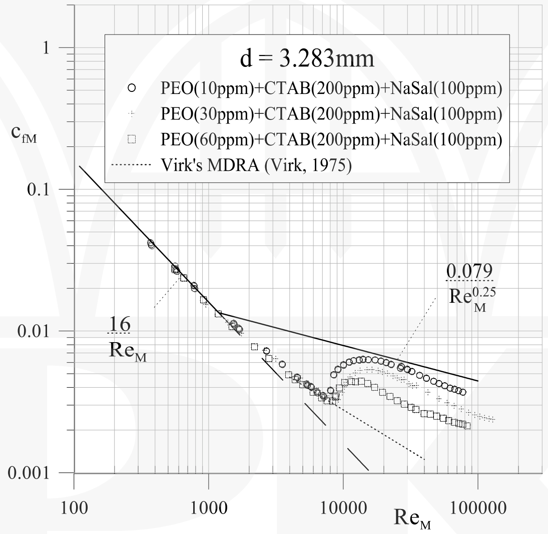

Fig. 8. Polymer concentration effect on the flow resistance curves of polymer-surfactant aqueous solutions

It should also be pointed out that addition to the micellar solution of even small amounts of high molecular weight polymer (about 10 ppm) causes a reduction of the non-Newtonian properties of the solution.

Experiment results indicate the influence of NaSal additive on drag reduction effect. Figure 9 presents a comparison of flow resistance curves of the pure polymer solution, the polymer-surfactant solution and the polymer-surfactant-salt solution.

It is clearly evident that with the addition of a small amount of electrolytes (e.g. salts or alcohols), a reformation of spherical micelles into threadlike micelles must proceeded. It leads to significant extension of the transitional zone B_1. Efficient drag reduction effect is observed within this zone of flow

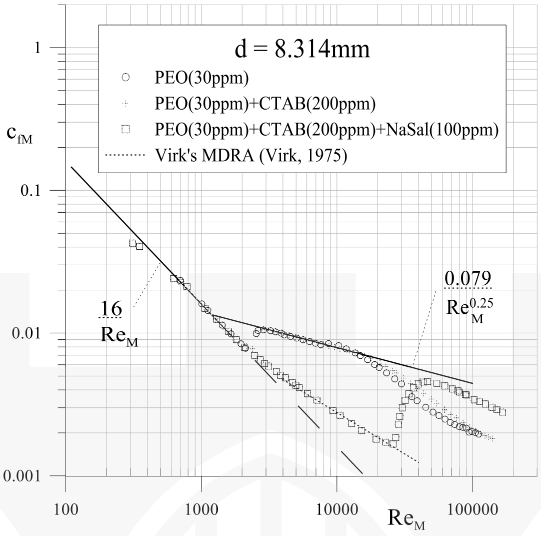

Fig. 9. The effect of NaSal additive on polymer-surfactant flow resistance curve

The results of drag reduction measurements analysis indicate the effect of pipe diameter influence on the drag reduction efficiency. Figure 10 illustrates the pipe diameter effect on the flow resistance curves of polymer-surfactant aqueous solutions.

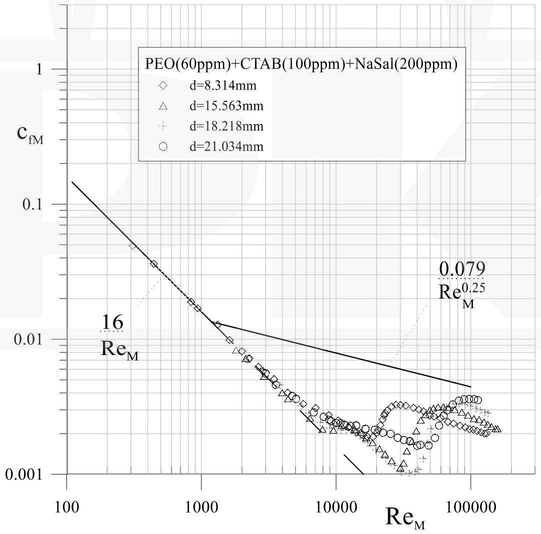

Fig. 10. Pipe diameter effect on the flow resistance curves of polymer-surfactant aqueous solutions

Increasing the pipe diameter d results in a clear extension of the stable transitional zone B_1 towards higher values of the Reynolds number. Moreover, decreasing the pipe diameter value d results in an increase of the drag reduction effect in the third additional turbulent range of flow C.

The experimental results reveal that polymer-micellar solution can be characterised by a lower susceptibility to mechanical degradation during flow or that its degradation can be almost unnoticeable in the analysed range of flow. Figure 11 illustrates a shift of the collapse of drag reduction effect toward greater values of Reynolds number caused by application of polymer and polymer-surfactant additives.

A pure PEO solution degrades very fast when it goes under high shearing conditions. A collapse of the drag reduction is gradually observed in such a case. Experimental results show a considerable increase of the Reynolds number value for which mechanical degradation of polymer and collapse of DR effect is observed in polymer-micellar solution.

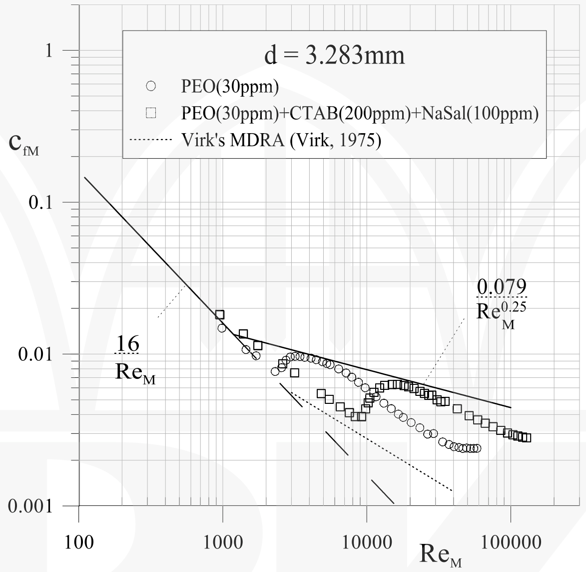

Fig. 11. Shift of the collapse of drag reduction effect toward greater values of Reynolds number caused by application of polymer and polymer-surfactant additives

5. Conclusions

Experimental study of drag reduction process induced by co-addition of polymer and surfactant with salt indicates that polymer-micellar aggregates are efficient drag reducers of the energy losses in straight pipe flow. Analyses of experimental data document that the simultaneous addition of surfactants and salt, together with high molecular polymers, causes a minor increase of flow resistance in the laminar range of flow compared to the analogue flow of pure solvent. It produces, however, a significant extension of the stable transitional zone between the laminar flow and the turbulent flow. The surfactant with salt additives has a major influence on the efficiency of the drag reduction in this zone.

Experimental results prove that the simultaneous addition of surfactant, salt and high molecular polymer leads to the occurrence of third significantly extended drag reduction zone in the turbulent range of flow. The dominant factors in that zone are the viscoelastic properties of the solution caused by the presence of polymer macromolecules, wherein an increase of the mass fraction of the polymer additive increases the efficiency of the drag reduction effect only in the turbulent range of flow.

The performed comparative studies presented that the analysed polymer-micellar solutions combine and intensify positive features of their purely polymer or purely micellar analogues, providing a more efficient drag reduction effect in a wider range of flow.

Under the experimental data, it can be hypothesised that aggregates, subjected to the shear stress, take orientation consistent with the aforementioned principle of minimum resistance. With an increasing value of the Reynolds number, internal friction forces stretch and extend the aggregates, leading to the laminarisation of the initial phase of the turbulent flow.

Therefore, it can be presumed that the rigid rod like/threadlike micelles, which create the core of the aggregates, are responsible for reducing the flow resistance in the extended transitional zone between the laminar and the turbulent flow.

The aggregates and micelles are responsible for the transmission of internal friction within the liquid. The value of the critical Reynolds number for which the transition to the turbulent zone is observed is greater for polymer-micellar solutions. This means that the stable transition zone is extended. The reason for such behaviour can be the partial disintegration of aggregates to original forms, i.e. micelles (formed from the surfactant) and macromolecules (formed from the polymer) due to a significant increase of the shear rate. From this moment, both micelles and macromolecules interact separately on the transported solution, causing a further drag reduction effect. Passing further in the turbulent range of flow micelles lose their orientation and no longer have a major impact on the drag reduction. A key role in this zone is played by the polymer. Not having undergone an earlier degradation, the polymer macromolecules still cause the flow reduction.

In drag reduction caused by the use of polymer-micellar solution, one cannot talk about the so-called *collapse of the drag reduction.* It occurs permanently over a wide range of Reynolds numbers. Nevertheless, in the turbulent zone, polymer macromolecules undergo a certain mechanical degradation. Decreasing the shear rate leads to the reconstruction of the internal structure of the solution. As a result of electrostatic or hydrophobic interaction, the recreated micelles are combined with the polymer chains by coiling around them. These chains are somewhat shorter and such newly created aggregates do not have the same rheological properties as the original ones. This results in a slight increase of the flow resistance in comparison with a freshly prepared solution.

Thee presented experimental results of the drag reduction effect are consistent in terms of qualitative analysis with proposed hypothesis, and confirm the described mechanism of the phenomenon in an indirect way.

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