Micellization of Polyoxyethylene–Polyoxypropylene Block Copolymers in Aqueous Polyol Solutions

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Abstract

The micellization of a representative polyoxyethylene-polyoxypropylene-polyoxyethylene (POE-POP-POE) amphiphilic block copolymer (Pluronic P105, EO₃₇PO₅₈EO₃₇) in aqueous solutions of the common excipients glucose, glycerol or ethanol, has been investigated as a function of solute (solvent) concentration, block copolymer concentration, and temperature. The formation of POE-POP-POE micelles is favored in the presence of glucose or glycerol, while ethanol has the opposite effect. ΔH° and ΔS° values derived from analysis of critical micellization concentration (CMC) data are both positive in all mixed aqueous polyol systems. ΔH° and ΔS° decrease slightly with increasing glucose or glycerol content, but increase significantly in the presence of ethanol. A 10- to 100-fold increase of the amphiphilic block copolymer solution viscosity was observed in the presence of glucose or glycerol above a certain temperature. This viscosity increase is indicative of micelle shape changes from spherical to elongated. The CMC and viscosity changes caused by glucose and glycerol are attributed to the enhanced dehydration of the POE block of the polymeric amphiphile. Glucose is more effective than glycerol, apparently due to its higher hydration number.

Keywords: block copolymer; Poloxamer; poly(ethylene oxide) (PEO); poly(propylene oxide) (PPO); glucose; formulation; excipient.

Introduction

The ability of amphiphiles to self-assemble in aqueous solutions is integral in a variety of products, e.g., pharmaceuticals, skin-care, hair-care, detergents, coatings and inks. Therefore, the elucidation of the self-assembly behavior of amphiphiles under different conditions is of great interest for industrial applications and also for fundamental considerations. Micellar solutions, which are the most common self-assembling systems, have been extensively researched. Several reports have considered solvent effects on micelle formation and structure, the solvent quality being a controlling factor for amphiphile self-assembly.¹

The most commonly examined solvent additives are alcohols and also polyols¹. Addition of alcohol to aqueous surfactant solutions can result in changes of, e.g., critical micellization concentration (CMC), critical micellization temperature (CMT), micelle molecular weight or association number, micelle radius, micelle shape, and ionization degree or surface density of micelle. These changes are attributed to a decrease of the solution dielectric constant caused by alcohols, and to alcohol penetration in the micelle hydrophobic interior^{1,2,3}. In the case of polyoxyethylene (POE)-containing nonionic surfactants, the dehydration of POE that is effected by added polyols becomes also important^{4,5,6}.

These factors lend complexity to aqueous surfactant systems containing alcohols. For example the effect of ethanol on the CMC of sodium dodecyl sulfate (SDS) or tetradecyltrimethylammonium bromide (TTAB) aqueous solution at 25 °C is non-monotonic: the CMC goes through a minimum at around 4.8 wt% ethanol and then increases with further increase of the ethanol content¹. On the other hand, in the case of POE(31)-dodecyl ether, the CMC simply increases with increasing ethanol content at 20 °C¹. The micelle size decreases and the micelles eventually disappear when sufficient amount of ethanol is added to SDS¹ (around 19 wt% ethanol) or to cetyltrimethylammonium bromide aqueous solution⁷ (around 80

vol% ethanol). In another example, the addition of glycerol to SDS^{8, 9} or TTAB¹⁰ aqueous solutions at 25 °C and to POE(8)-dodecyl ether¹¹ aqueous solution in the temperature range 25 – 35 °C leads to an increase in CMC. Moreover, the addition of glycerol to POE(8)-hexadecyl ether results in a shape change of the micelles from spherical to rod-like⁴.

We have an on-going interest in our research group on solvent quality effects on the conformation and supramolecular organization of polymeric amphiphiles such as polyoxyethylene-polyoxypropylene-polyoxyethylene (POE-POP-POE) block copolymers (which are commercially available as Pluronics or Poloxamers), poly(dimethylsiloxane)-graft-polyether copolymers, and polysaccharides (e.g., dextran, cellulose ethers). We have shown that the structural polymorphism of polymeric surfactants is richer than that of typical, low molecular weight surfactants^{12, 13}. Even in dilute solutions, polymeric surfactants have the potential to exhibit complex structures such as flower-like or star-like assemblies¹⁶ due to the conformational flexibility conferred by their higher molecular weight and corresponding length.

We have previously reported on the effects of polar organic solvents such as formamide, ethanol, and glycerol on the self-assembly of a POE-POP-POE block copolymer (Pluronic P105, EO₃₇PO₅₈EO₃₇) in aqueous solutions, determined from analysis of small-angle neutron scattering (SANS) measurements^{5, 15}. We found that the addition of formamide or ethanol led to a decrease in the micelle size and the polymer volume fraction in the micelle corona and core, and an increase in the CMC, while glycerol caused the opposite trend^{5, 15}. Other groups have reported the effect of 1-butanol on Pluronic F127 (EO₉₉PO₆₅EO₉₉) aqueous solutions¹⁶, and of 1-pentanol on Pluronic P103 (EO₁₇PO₆₀EO₁₇), P105 (EO₃₇PO₅₈EO₃₇), and P108 (EO₁₃₂PO₅₀EO₁₃₂) aqueous solutions¹⁷. Both 1-butanol and 1-pentanol decrease the CMC and solubilize in the micelle core¹⁷, in agreement with our observations.

We have also reported on the effects of 2-propanol, ethanol, formamide and glycerol on

micelles formed by poly(dimethylsiloxane)-graft-polyether copolymers in aqueous solutions. The micelle radii, micelle association numbers, and polymer volume fractions in the micelle corona and core decreased with increasing 2-propanol, ethanol, or formamide content. On the contrary, the addition of glycerol led to an increase of the micelle association number and caused a micelle shape change from sphere to ellipse⁶. Similar shape changes in poly(dimethylsiloxane)-graft-polyether micelles have been reported upon the addition of glucose, 2-butoxyethanol, and polyoxyethylene¹⁸. It is notable that we found a good correlation between the CMC in the presence of various solvents and the component of the solvent solubility parameter (δ) which accounts for hydrogen bonding^{19,20}.

Here we focus our attention on polyols such as glucose and glycerol which are widely used as excipients in pharmaceutical, cosmetic, and food formulations^{21,22}. We examine the effects of these polyols on the micellization in water of a representative POE-POP-POE block copolymer (Pluronic P105, $\text{EO}_{37}\text{PO}_{58}\text{EO}_{37}$). In particular, we present information on (i) micelle formation, (ii) thermodynamics of micellization, and (iii) micelle solution properties in aqueous glucose or glycerol solutions, as well as in aqueous mixtures of glucose and ethanol.

Materials and Methods

Materials

The Pluronic P105 polyoxyethylene-polyoxypropylene-polyoxyethylene (POE-POP-POE) block copolymer was obtained from BASF Corp. and was used as received. According to the manufacturer it has molecular weight of 6500 and 50 wt% PEO content and can thus be represented as $\text{EO}_{37}\text{PO}_{58}\text{EO}_{37}$. Among the various POE-POP-POE block copolymers available commercially, Pluronic P105 is of intermediate hydrophobic/hydrophilic balance and molecular weight. Not coincidentally it exhibits a rich phase behavior in the presence of water

and/or non-aqueous polar solvents²³⁻²⁵. D(+)-glucose monohydrate (>99.5%) was purchased from Fluka Chemical Corp., Milwaukee, WI. Glycerol anhydrous (>99.5) was purchased from J. T. Baker, Phillipsburg, NJ. Ethyl alcohol (99.5%) was purchased from Pharmco Products Inc., Brookfield, CT. Millipore-filtered water was used for all samples, which were prepared by weighing appropriate amounts of polymer, solute and water. Appropriate time was allowed for thermodynamic equilibration of the samples. Chemical formulas for the molecules considered here are shown in Fig. 1, and physicochemical parameters are presented in Table 1.

Light scattering

The light scattering intensity of samples was measured with a Brookhaven BI-200SM goniometer (equipped with a Lexel model 95 argon ion laser operating at 514 nm) at 90° detection angle at temperatures varying in the range 5 - 45 °C. Previously equilibrated samples were kept an hour at a specific temperature before measurements. The sample compositions are the following: Pluronic P105 content = 1 or 8 wt%, solute or solvent (glucose monohydrate, glycerol, or ethanol) content = 0, 20, 30, 40, or 60 wt%, and the remainder is water.

Viscosity

Viscosities of aqueous Pluronic P105 solutions were measured with a Cannon-Fenske routine type viscometer at the temperature range 7 - 60 °C²⁰. The reproducibility of viscosity values was typically $\pm 3\%$. Above certain temperatures the viscosities of these solutions increased dramatically (more than 10-fold), and the measurements in this case were subject to bigger error. The sample compositions that we considered are: 1 or 8 wt% Pluronic P105, 0, 20, 30, or 40 wt% glucose monohydrate or glycerol, or 5, 10 wt% ethanol, with the remainder being water. The reported relative viscosity denotes the viscosity of the aqueous Pluronic P105

solutions divided by the viscosity of the correspondent solvents (consisting of aqueous solutions of glucose, glycerol, or glucose + ethanol, or plain water).

Phase behavior

We have already reported ternary isothermal (25 °C) phase diagrams for Pluronic P105 - water - glucose, glycerol, or ethanol systems²⁴. Normal (“oil”-in-“water”) isotropic micellar solutions as well as micellar cubic, normal hexagonal, normal bicontinuous cubic, and lamellar lyotropic liquid crystalline (LLC) phases have been identified in these phase diagrams. The LLC structures “dissolve” with increasing ethanol content above 25 %. It is notable that, with increasing glucose or glycerol content relative to water, the composition range of the normal hexagonal (cylindrical) LLC region expands toward lower block copolymer contents. This signifies a decrease in interfacial curvature (from sphere to cylinder). On the basis of these findings²⁴, we can expect that at elevated temperatures the formation of normal hexagonal lyotropic liquid crystalline structure will take place at lower block copolymer content and/or glucose or glycerol content.

Motivated by the above, we checked the samples under polarized light for possible optical anisotropy, indication of hexagonal or lamellar LLC structure. All samples examined and reported here were transparent and one-phase in the temperature range 7 – 60 °C. Some birefringence was observed only at the composition Pluronic P105 (8 wt%) - glucose monohydrate (40 wt%) - water (52 wt%), at 55 and 60°C (we do not report data for these conditions here). This slight birefringence became more pronounced when the sample was shaken by hand. This could be suggestive of the formation of a nematic phase of elongated micelles^{26,27}, which may be intermediate between the micellar solution and the hexagonal LLC phase.

Results and Discussion

Micelle formation

In aqueous solution POP-POE-POP block copolymers can self-assemble into micelles with the core dominated by the relatively hydrophobic POP blocks and the corona dominated by hydrated POE blocks. The aqueous solubility of these blocks is dependent on temperature, therefore the self-assembly of POE-POP-POE block copolymers is very sensitive to temperature, contrary to that of typical nonionic surfactants^{28, 29}. Such amphiphilic block copolymers can form micelles above a certain solution temperature (CMT), in addition to forming micelles above a certain block copolymer concentration (CMC). Thus one can ascertain the micelle formation from either CMT or CMC measurements³⁰. In this study we conducted CMT measurements because they have the advantage of using the same samples at varying temperature, thus eliminating a possible source of experimental uncertainty. We determined the CMT from changes of the light scattering intensity vs. temperature, since the micelles scatter light much more strongly than the unassociated polymers (unimers)³⁰.

The CMTs of ternary Pluronic P105 (1 or 8 wt%) - solute or solvent (glucose monohydrate, glycerol, or ethanol) (0, 20, 30, 40 wt%) - water solutions are reported in Fig. 2. The lines connecting the CMT-CMC points can be viewed as the micellization phase boundaries³⁰. At temperatures and block copolymer concentrations below the micellization boundary, the block copolymers do not associate (but remain free in solution as unimers). At temperatures and concentrations above the micellization boundary, the block copolymers self-assemble to form micelles (that are in equilibrium with unimers). In the case of the glucose and glycerol solutions, the micellization boundaries shift toward the low left corner of the diagrams, whereas ethanol has the opposite effect. This demonstrates that glucose and glycerol

promote the formation of micelles, but ethanol does not.

The CMT decrease with increasing glucose content in the systems considered here is consistent with previously reported cases: the addition of glucose to SDS^{31, 32}, t-octylphenoxypolyethoxyethanol (Triton X-100)^{31, 32}, polyoxyethylene sorbitanmonolaurate (Tween 20)³², or poly(dimethylsiloxane)-graft-polyether¹⁹ aqueous solutions led to a decrease in CMC, a shift to lower temperature of the gel-sol transition for poly(2-ethyl-2-oxazoline)-poly(ϵ -caprolactone) block copolymer aqueous solutions³³, and a lowering of the cloud point of polyoxyethylene (PEG 20000) aqueous solution³⁴. More specifically, addition of 5 wt% glucose in aqueous surfactant solutions at 25 °C caused a CMC decrease from 0.029 to 0.017 wt% for SDS, from 0.037 to 0.025 wt% for Tween 20, and from 0.032 to 0.026 wt% for Triton X-100³². This tendency may be attributed to the dehydration of POE caused by glucose^{4, 5, 6, 19, 35}.

The POE-POP-POE block copolymer CMT decrease with increasing glycerol content is consistent with previous research on the same system (up to 20 vol% glycerol)⁵, but opposite to what has been observed for typical surfactants: the addition of glycerol to SDS^{8, 9}, TTAB¹⁰ or POE(8)-dodecyl ether¹¹ aqueous solutions caused an increase in CMC. This increase in CMC upon adding glycerol can be due to the weakening of the hydrophobic interactions³¹ following a decrease of the solution dielectric constant¹. In the case of POE-POP-POE block copolymer aqueous solutions, POE dehydration effected by glycerol^{4, 5, 6, 19, 35} appears more effective than a possible weakening of the hydrophobic interactions³¹, and leads to a CMC or CMT decrease.

Comparison of glucose and glycerol effects on micellization relative to the number of OH groups

The OH groups of solutes or solvents present in aqueous solutions play an important

role on micellization. It has been reported that the effects of alcohols (methanol, ethylene glycol, or glycerol) on the CMC of SDS aqueous solutions depend on the number of OH groups and not on the number of alcohol molecules when their concentration are relatively low (around 5 wt%). For the same number of OH groups, the increase in CMC follows the sequence: methanol > ethylene glycol > glycerol⁹.

To probe the role of OH groups on the effect of glucose or glycerol on the CMT in Pluronic P105 aqueous solutions, we plot in Fig. 3 the CMTs against glucose or glycerol content expressed in units of wt%, mol%, or OH group mol%. Glucose had a stronger effect on CMT compared to glycerol, especially when its concentration is expressed in mol% or OH mol%. For example, the addition of around 20 OH mol% of glucose in 8 wt% Pluronic P105 aqueous solution decreased the CMT from 18 to 0 °C, whereas the same amount of OH groups of glycerol decreased the CMT to 5 °C (Fig. 3 (c)). These effects can be attributed to the stronger dehydration caused by glucose. It has been reported that: (i) the hydration number (i.e., the average number of water molecules binding to a solute sufficiently strongly as to become part of it) of glucose (2.8 ± 0.5) is higher than that of glycerol (2 ± 0.5)³⁵, (ii) the addition of glucose to Triton X-100 aqueous solutions lowers the cloud point more than glycerol³⁶.

The relative contributions of the OH groups of glucose or glycerol to the solution properties reported for amphiphile systems are relevant to aqueous solutions of biopolymers (proteins), e.g., the change in preferential hydration (connected to the number of additional water molecules that interact with protein) upon unfolding ribonuclease a and hen egg white lysozyme in aqueous glucose or glycerol solutions³⁷, and to the bovine serum albumin gelation temperature changes in aqueous glycerol or sorbitol solutions³⁸. It has been shown that the unfolding changes in preferential hydration that are observed in glucose solutions were three times higher than those in glycerol solutions, and were roughly proportional to the OH group concentration³⁷.

Also it has been reported that the bovine serum albumin gelation temperature increased by +3°C or +10°C by adding 40 wt% glycerol or sorbitol, respectively, to the aqueous system. When compared in terms of OH groups, these gelation temperature changes occur at similar concentrations, 12.9 M for glycerol and 13.2 M for sorbitol solutions³⁸. This suggests that OH group numbers alone cannot explain the difference between glucose and glycerol. This can involve a stronger dehydration effect through the combined OH groups of glucose or glycerol rather than their overall OH group number in the system.

Thermodynamics of micellization

The CMT-CMC data for Pluronic P105 in the mixed aqueous solvents (reported in Fig. 2) can be further used to extract information on the thermodynamics of micellization^{15,30}. The standard free energy change for the transfer of 1 mole of amphiphile from solution to the micellar phase (free energy of micellization, ΔG°), assuming an equilibrium between unimers and micelles, is given by:

$$\Delta G^\circ = R T \ln(X_{CMC}) \quad (1)$$

where R is the ideal gas constant, T the absolute temperature, and X_{CMC} the critical micellization concentration (expressed in mole fraction units) at temperature T. ΔG° needs to be negative for thermodynamically stable micelles to form. The more negative the ΔG° , the stronger becomes the driving force for micellization. With increasing glucose or glycerol content (up to 40 wt%) in the solution, ΔG° becomes more negative at a given temperature (Fig. 4). In the case of ethanol (up to 20 wt%), the change of ΔG° follows the opposite trend.

The standard enthalpy of micellization (ΔH°) and the standard entropy of micellization (ΔS°) can be calculated from ΔG° vs. T curves (shown in Fig. 4) using the following equation (assuming that ΔH° is independent of temperature, which is reasonable for a small temperature

range):

$$\Delta G^\circ = \Delta H^\circ - T \Delta S^\circ \quad (2)$$

Micelle formation is an enthalpically disfavored process when ΔH° is positive. In this case, a positive ΔS° must be the driving force for micellization. The ΔH° and ΔS° values are both positive and decrease with increasing glucose or glycerol content: from 258 kJ/mol and 0.956 kJ/mol·K in plain water, to 179 kJ/mol and 0.721 kJ/mol·K at 30 wt% glucose monohydrate, respectively. For 30 wt% glycerol systems, the ΔH° and ΔS° values were 180 kJ/mol and 0.772 kJ/mol·K, respectively (Fig. 5).

The ΔH° and ΔS° values decrease with increasing glucose or glycerol contents (Fig. 5) at a constant ratio $\Delta H^\circ/\Delta S^\circ$. This ratio is known as enthalpy-entropy compensation^{9, 39-42}. According to Lumry and Rajender, the micellization process consists of two parts, the “solvation part” and the “chemical part”³⁹⁻⁴¹. The slope of the compensation plot (ΔH° vs. ΔS°) provides information on solute-solute and solute-solvent interactions as a measure of the “solvation part” of the micellization process, and the intercept gives information on solute-solute interactions as an index of the effectiveness of the “chemical part” of the micelle formation^{40, 41}. If both the “solvation part” and the “chemical part” of the micellization process are the same, the $\Delta H^\circ/\Delta S^\circ$ values fall on a straight line⁴². This has been the case for the micellization of three polyoxyethylene(4, 6, or 8) dodecyl ethers in aqueous solutions⁴². As shown in Fig. 8, the $\Delta H^\circ/\Delta S^\circ$ values for the micellization of Pluronic P105 POE-POP-POE block copolymer in aqueous glucose monohydrate or glycerol (0, 20, 30 wt%) solutions all fall on the same straight line, indicating the same micellization mechanism in both glucose and glycerol solutions.

Micelle solution viscosity

With increasing temperature, the micelle shape attained by typical POE-containing

nonionic amphiphiles in aqueous solution may change from spherical to prolonged, because the interfacial curvature becomes less positive due to the dehydration of POE groups⁴³. Such micelle shape changes have been connected to changes in the viscosity of the micellar solution⁴⁴⁻⁴⁹. For example, the observed increase by a factor of 10 of the specific viscosity of 0.5 - 4 wt% Pluronic P85 (EO₂₅PO₄₀EO₂₅) in 5.5 wt% KF aqueous solution with increasing temperature from 35 to 41 °C has been attributed to a micelle shape change from sphere to rod which was independently established by sedimentation and light scattering measurements⁴⁴. In another example, intrinsic viscosities for Pluronic P85 (EO₂₅PO₄₀EO₂₅) or L64 (EO₁₃PO₃₀EO₁₃) in aqueous salt (KBr, KCl, or KF) solutions showed a steep rise with increasing temperature at about 10 - 20 °C below the cloud point⁴⁵. Non-Newtonian behavior such as shear thickening or shear thinning has also been used as evidence for the existence of rod-like micelles⁴⁶⁻⁴⁹. Shear thinning behavior due to rod-like micelle shape has been reported in 50 wt% sucrose laurate⁴⁷ or cetyltrimethylammonium bromide aqueous solutions⁴⁸, and both shear thinning and shear thickening behavior have been reported in polyoxyethylene(7)-dodecyl, -tetradecyl, or -hexadecyl ether aqueous NaCl solutions⁴⁶.

Motivated by the above, we probed a possible POE-POP-POE block copolymer micelle shape change in aqueous glucose or glycerol solutions using viscosity measurements. Fig. 7 shows relative viscosity (in the temperature range 7 – 60 °C) for Pluronic P105 (1 or 8 wt%) - water solutions, Pluronic P105 (1 or 8 wt%) - glucose monohydrate (20 or 40 wt%) - water solutions, and Pluronic P105 (1 or 8 wt%) - glycerol (20, 40, 60 wt%) - water solutions. The relative viscosities for binary Pluronic P105 aqueous solutions and ternary Pluronic P105 - 20 wt% glycerol - water solutions remained almost constant relative to temperature (or decreased slightly). Whereas the viscosities for the systems which have higher glucose or glycerol content increased steeply beyond a certain temperature. For 1 wt% Pluronic P105 solutions, the

relative viscosity increases more than ten-fold starting at 50 °C (in 40 wt% glucose monohydrate or 60 wt% glycerol). For 8 wt% Pluronic P105 solutions, the relative viscosity increases by almost two orders of magnitude, starting at 55 °C (20 wt% glucose monohydrate), 40 °C (40 wt% glucose monohydrate), 55 °C (40 wt% glycerol), and 40 °C (60 wt% glycerol).

The lack of change of the relative viscosity relative to temperature is indicative of the preservation of a spherical micelle shape in this temperature range^{5, 49, 50}, whereas the significant increase in the relative viscosity above a certain temperature may be connected to a micelle shape change from sphere to rod⁴⁴⁻⁴⁸. In plain water, the Pluronic P105 block copolymer micelles are spherical in this temperature range up to 60 °C. According to the literature, the micelles remain spherical up to 90 °C for 5 - 8.9 wt% Pluronic F88 (EO₁₀₃PO₃₉EO₁₀₃) aqueous solutions^{51, 52}, and up to 95 °C for 12 wt% Pluronic F127 (EO₉₉PO₆₅EO₉₉)⁵³. A micelle shape change from sphere to rod occurred above 56 °C in 10 wt% Pluronic P94 (EO₂₈PO₄₈EO₂₈) aqueous solutions⁵⁴, and above 70 °C in 1 wt% Pluronic P85 (EO₂₅PO₄₀EO₂₅)⁵⁵.

The presence of relatively high glucose or glycerol contents enabled Pluronic P105 micelle shape changes to occur in the temperature range 40 – 55 °C. These temperatures are relatively low compared to the temperatures required for micelle shape transition in the case of aqueous Pluronic P85 and P94 solutions, but are similar to the temperatures at which rod-like POE-POP-POE block copolymer micelles form in water in the presence of salts. Rod-like micelles of Pluronic F88 (EO₁₀₃PO₃₉EO₁₀₃) appeared at 42 °C by adding 6.1 wt% K₂CO₃⁵², of Pluronic P85 (EO₂₅PO₄₀EO₂₅) at 38 °C in the presence of 5.5 wt% KF⁴⁴, and of Pluronic L64 (EO₁₃PO₃₀EO₁₃) and P85 (EO₂₅PO₄₀EO₂₅) at 15 – 20 °C below the cloud point by adding salts such as KBr, KCl, and KF⁴⁵.

These micelle changes that occur at relatively low temperatures (around 40 °C) are triggered by the addition of solutes. The synergistic effects of glucose or glycerol and

temperature have been reported in the case of poly(dimethylsiloxane)-graft-polyether copolymer¹⁹ or polyoxyethylene cetyl ether aqueous solutions⁴. The addition of glucose resulted in an oblate ellipsoidal shape for the micelles formed by a poly(dimethylsiloxane)-graft-polyether copolymer¹⁹. The addition of glycerol to POE cetyl ether aqueous solution caused an increase of the rod-length of the micelles at first, followed by a decrease when approaching the cloud point temperature⁴. Both these cases have been attributed to the dehydration of POE by glucose or glycerol^{4, 5, 6, 19, 35}. Therefore, the formation by Pluronic P105 POE-POP-POE block copolymer of rod-like micelles in aqueous glucose or glycerol solutions at elevated temperatures can be attributed not only to the increased hydrophobicity of both POP and POE blocks caused by heating, but also to the further dehydration of POE by glucose or glycerol.

Comparison of glucose and glycerol effects on viscosity relative to the number of OH groups

To investigate the role of OH groups on the effect of glucose or glycerol in the micelle shape change observed in 8 wt% Pluronic P105 aqueous solutions, we plot in Fig. 8 the temperature at which possible micelle shape changes occurred against the glucose or glycerol content expressed in units of wt%, mol%, or OH group mol%. Glucose shows more pronounced effects than glycerol on the solution viscosity at the same concentration and temperature. For example, the addition of around 30 OH mol% of glucose in 8 wt% Pluronic P105 aqueous solution was necessary for the micelle shape change to occur at 40 °C, whereas around 80 OH mol% of glycerol was needed in order to have a micelle shape change at the same temperature (Fig. 8 (c)). This can be attributed to the stronger dehydration effect (through mainly OH groups) of glucose than that of glycerol, the same reason behind the observed trends

on CMT discussed previously. In fact, the slopes of the micelle shape change temperature and the CMT relative to the glucose or glycerol content are similar (Fig. 8).

This dehydration effect is strong, as attested by the fact that significant relative viscosity increase starting at 40 °C can still be observed, even following the addition of 10 wt% ethanol to aqueous solution of 8 wt% Pluronic P105 and 40 wt% glucose monohydrate (Fig. 9).

Conclusions

The effects of glucose, glycerol, or ethanol on the micellization of a representative POE-POP-POE amphiphilic block copolymer (Pluronic P105) in aqueous solutions were investigated in the temperature range 5 – 60 °C. The work reported here furthers our understanding of self-assembly of amphiphiles in mixed systems and is also relevant in diverse applications such as pharmaceuticals, skin-care, hair-care, detergents, coatings and inks, where (i) product function and viscosity are often intertwined, and (ii) polyethoxylates and polyols (the types of molecules that we considered here) are very common ingredients. This is one of very few studies concerned with effects of glucose on amphiphiles. The findings are also relevant to biological applications where this polyol is often used.

Micelle formation was favored in aqueous solutions containing glucose or glycerol. Ethanol had the opposite effect and the micelles disappeared above 40 wt% ethanol. ΔH° and ΔS° values derived from CMT-CMC data are both positive in the presence of glucose and glycerol, and decrease slightly with increasing solute/solvent content at a constant ratio. The $\Delta H^\circ/\Delta S^\circ$ ratio (known as enthalpy-entropy compensation) falls on the same line for both systems, therefore, both glucose and glycerol affect the micelle formation by the same mechanism.

Significant changes on the relative viscosity suggest that a micelle shape change from sphere to rod takes place at higher content glucose or glycerol aqueous solutions in the

temperature range 40 to 55 °C. These phenomena are attributed to a dehydration of the POE block of the amphiphile caused by glucose or glycerol, beyond the dehydration effected by the increase in temperature. The temperature above which a micelle shape change occurred decreased with increasing glucose or glycerol content, similarly with the CMT.

Glucose has a greater impact on the CMT and the micellar shape change temperature compared to glycerol, at a given concentration expressed in wt%, mol% or OH mol%. In fact, the addition of 10 wt% ethanol (which tends to destabilize the micelles) cannot overcome the effects of 40 wt% glucose monohydrate on the micelle structure of 8 wt% Pluronic P105.

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Table 1. Kaizu & Alexandridis

Table 1. Physicochemical parameters of the solute and solvents used in this study.

Solvent Solute	m_w^a	Density ^{b,c} (g/cm ³)	Dielectric constant ^{b,c}	Dipole moment ^d	log P ^e	Solubility Parameter ^f (MPa ^{1/2})
Water	18.01	0.9982	78.5	3.11	-1.38	47.8
Glucose	180.16	1.5620		14.1	-3.29	
Glycerol	92.10	1.2567	40.1	2.68	-2.55	36.2
Ethanol	46.07	0.7873	24.3	1.69	-0.32	26.5

^a m_w : molecular weight

^b density and dielectric constant values are at 25 °C

^c data from Weast [56]

^d data from McClellan [57]

^e log P: logarithm of the octanol/water coefficient (data from refs [58] and [59])

^f data from Hansen [60]

Fig. 1. Kaizu & Alexandridis

Figure 1. Chemical structures of the amphiphilic block copolymer and polyols used in this study.

Fig. 2. Kaizu & Alexandridis

Figure 2. Temperature-concentration micellization boundaries for Pluronic P105 amphiphilic block copolymer in aqueous solutions of (a) glucose monohydrate (0, 20, 30, 40 wt%), (b) glycerol (0, 20, 30, 40 wt%), or (c) ethanol (0, 20 wt%).

Fig. 3. Kaizu & Alexandridis

Figure 3. CMT in aqueous Pluronic P105 solutions plotted as a function of glucose or glycerol content, expressed in different units: (a) wt%, (b) mol%, and (c) OH group mol%.

Fig. 4. Kaizu & Alexandridis

Figure 4. Free energy (ΔG°) of Pluronic P105 amphiphilic block copolymer micelle formation in aqueous solutions containing: (a) glucose monohydrate (0, 20, 30 wt%), (b) glycerol (0, 20, 30 wt%), or (c) ethanol (0, 20 wt%).

Fig. 5. Kaizu & Alexandridis

Figure 5. Enthalpy (ΔH°) and entropy (ΔS°) of Pluronic P105 micellization in aqueous solution plotted as a function of solute or solvent wt% content: (a) glucose monohydrate (0, 20, 30 wt%), (b) glycerol (0, 20, 30 wt%), (c) ethanol (0, 20 wt%).

Fig. 6. Kaizu & Alexandridis

Figure 6. Enthalpy (ΔH°) / entropy (ΔS°) compensation for the micellization of Pluronic P105 in aqueous solutions containing glucose monohydrate or glycerol (0, 20, 30 wt%).

Fig. 7. Kaizu & Alexandridis

Figure 7. Relative viscosity plotted as a function of temperature for the systems:

(a) Pluronic P105 (1 wt%) - glucose monohydrate (0, 20, 40 wt%) - water.

(b) Pluronic P105 (1 wt%) - glycerol (0, 20, 40, 60 wt%) - water.

(c) Pluronic P105 (8 wt%) - glucose monohydrate (0, 20, 40 wt%) - water.

(d) Pluronic P105 (8 wt%) - glycerol (0, 20, 40, 60 wt%) - water.

Fig. 8. Kaizu & Alexandridis

Figure 8. Micelle shape change temperature and CMT of 8 wt% Pluronic P105 in aqueous glucose or glycerol solutions, plotted as a function of the glucose or glycerol content (expressed in different units): (a) wt%, (b) mol%, (c) OH group mol%.

Fig. 9. Kaizu & Alexandridis

Figure 9. Relative viscosity of Pluronic P105 (8 wt%) - glucose monohydrate (40 wt%) - ethanol (0, 5, 10 wt%) - water solutions plotted as a function of temperature.