PEO-PPO-PEO Triblock Copolymers In Aqueous Solutions:
Micellization & Self-Assembly Into Fiberlike Aggregates

by

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This is to certify that I have examined this copy of a MS thesis by

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ABSTRACT

Physicochemical properties of aqueous poly (ethylene oxide)-poly (propylene oxide)-poly(ethylene oxide) (PEO-PPO-PEO) triblock copolymers, commonly known as Pluronics, have long been studied. The phase diagram of micellar structures is well-known and these structures were exploited in various applications ranging from drug delivery systems to mesoporous metal oxide synthesis.

In this thesis, micellization and the self-assembly of Pluronic F127, $(PEO)_{106}$-$(PPO)_{70}$-$(PEO)_{106}$ in dilute aqueous solutions have been investigated. Formation of fiberlike aggregates below the critical micelle temperature (T_{cm}) has been observed for the first time. To understand the factors affecting this unexpected self-assembly into fiberlike aggregates, micellization of Pluronic F127 has been systematically studied by Dynamic Light Scattering (DLS) as a function of polymer concentration and in the presence of five different sodium salts. T_{cm} decreased linearly with salt concentration in aqueous solutions containing kosmotropic anions CO_3^{2-}, CH_3COO^- and Cl^-. In the presence of chaotropic SCN^- and I^- anions, T_{cm} increased with salt concentration. Similar trends have also been observed for Pluronic F68, $(PEO)_{80}$-$(PPO)_{30}$-$(PEO)_{80}$, which showed ~30 ^oC higher T_{cm} compared to Pluronic F127 due to its higher PEO content.

The formation of water-insoluble self-assembled fiberlike aggregates of Pluronic F127 below T_{cm} is difficult to understand considering the facts that both PEO and PPO are water soluble. Unexpected clustering of PEO in aqueous solutions has previously been reported. To understand whether PEO clustering plays any role in the formation of fiberlike aggregates, aqueous solutions of PEO having five different molecular weights were also investigated by DLS. A transition from good solvent to theta solvent conditions with increasing

temperature was observed at ~40-45 ^{o}C. In some experiments, aggregation of PEO was also observed in the same temperature range. Though it is not possible to relate these observations directly to self-assembly of fiberlike aggregates at 25 ^{o}C, the early stages of such PEO clustering may be inducing the seeds of self-assembly.

ÖZET

Pluronik olarak da adlandırılan sulu poli(etilen oksit)-poli(propilen oksit)-poly(etilen oksit) (PEO-PPO-PEO) üçlü blok kopolimerlerinin fizikokimyasal özellikleri uzun zamandan beri araştırılmaktadır. Misel yapılara ait faz diagramı bilinmektedir ve bu yapılar ilaç salınım sistemlerinden mezogözenekli metal oksit sentezine kadar birçok uygulamada kullanılmaktadır.

Bu tezde pluronik F127 $(PEO)_{106}$-$(PPO)_{70}$-$(PEO)_{106}$ nın seyreltik sulu çözeltilerinde miselizasyon ve kendinden yapılanma özellikleri incelendi. İlk kez kritik miselleşme sıcaklığının altında fiber yapıda çökelti oluşumu gözlendi. Bu fiber yapıdaki çökeltilerin beklenmeyen kendinden yapılanmalarını etkileyen faktörleri anlayabilmek için Pluronik F127nin miselizasyon davranışı Dinamik Işık Saçılımı (DLS) tekniği ile, farklı polimer konsantrayonu ve beş farklı sodium tuzu ortamında, sistematik bir şekilde incelendi. Sulu çözeltilerde kosmotropik CO_3^{2-}, CH_3COO^- ve Cl^- anyonların varlığında kritik miselizasyon sıcaklıklarının tuz konsantrasyonlarının artışı ile lineer olarak azaldığı bulundu. Kaotropic anyonların varlığında ise SCN^- ve I^- tuz konsantrasyonalrının artışı ile kritik miselleşme sıcaklıklarının arttığı gözlemlendi. Pluronik F68 $(PEO)_{80}$-$(PPO)_{30}$-$(PEO)_{80}$ için de, Pluronik F127 ile kıyaslandığında yüksek PEO miktarı sebebiyle yaklaşık 30 derece daha yüksek sıkcalıklarda görülmek ile birlikte, benzer bir davranış görüldü.

PEO ve PPO'nun suda çözünür olması Pluronik F127' nin kritik miselleşme sıcaklığının altında oluşturduğu suda çözünmeyen fiber şekilde çöken kendinden yapılanmaların anlaşılmasını zorlaştırmaktadır. Literatürde PEO'in sulu çözeltilerde oluşturduğu beklenmeyen yapılanmalar ile ilgili çalışmalar bulunmaktadır. Bu çalışmada, PEO yapılanmasının fiber şekilli çökelti oluşumuna etkisini anlamak amacıyla beş farklı moleküler ağırlığa sahip sulu PEO çözeltileri de DLS ile incelendi. Yaklaşık 40-45 ^oC derece

sıkcalıklarda suyun PEO için iyi solventten teta solvent durumuna geçtiği gözlendi. Bazı deneylerde PEO çökeltilerinin aynı sıcaklık aralığında oluştuğu tespit edildi. Bu gözlemleri, 25 ^{o}C' de kendinden yapılanan fiber şekilli çökelti oluşumu ile doğrudan ilişkelendirmek mümkün olmasa da, PEO' in başlangış safhasındaki bu çeşit oluşumlarının kendinden yapılanma için bir tetikleyici olduğu düşünülmektedir.

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NOMENCLATURE

CMT/ T_{cm} : Critical Micellization Temperature

CMC: Critical Micellization Concentration

DLS: Dynamic Light Scattering

FT-IR: Fourier Transform Infrared Spectroscopy

LCST: Lower Critical Solution Temperature

M_w: Molecular Weight

N: Number of Monomers

PEO: Poly(ethylene oxide)

PPO: Poly(propylene oxide)

R_g: Radius of Gyration

R_h: Radius of Hydration

SEM: Scanning Electron Microscopy

SANS: Small Angle Neutron Scattering

UCST: Upper Critical Solution Temperature

1. Introduction

This chapter gives an overview of general self-assembly phenomena, and then discusses the amphiphilic small molecules and block copolymers. First part of this chapter summarizes the previous theoretical and experimental studies made on aqueous poly (ethylene oxide) (PEO) and poly (propylene oxide) (PPO) homopolymer solutions. Second part includes of the self-assembly phenomenon of PEO-PPO-PEO block copolymers and factors effecting them, which are used in the next chapters of this thesis.

Section 1.1 gives the fundamental properties of amphiphilic small molecules and blocks copolymers and compare to each other. Section 1.2 describes the poly (ethylene oxide) and poly (propylene oxide) homopolymers and their characteristic properties in water. The studies made on clustering of PEO below lower critical solutions temperature are discussed. The insight from these studies is used to understand PEO-water interactions. In the discussion section, this information is used to understand the changes of the sizes of single PEO molecule in water upon temperature change. Section 1.3 gives the general information on PEO-PPO-PEO block copolymers and their applications. Section 1.4 describes the self-assembly of amphiphilic molecules and their possible resulting morphologies. Section 1.5 explains the dominant driving forces of self-assembly in water for PEO-PPO-PEO triblock copolymer; hydrogen bonding and the hydrophobic effect. Section 1.6 gives a brief review of the studies made on PEO-PPO-PEO micellization in water and factors affecting this phenomenon.

1.1. Amphiphilic Small Molecules and Block Copolymers

Molecules which have an affinity for two different types of environments are called amphiphilic molecules. This dual character is gained by the molecule via the covalently bonded parts, which possesses different chemical characters and different interaction properties with solvents. When the solvent is water, these two parts are specifically called hydrophilic and hydrophobic parts. The hydrophilic parts refer to the part that favorably interacts with water; on the other hand the hydrophobic parts show similar affinity to rather non-polar environments. Small molecules as well as large block copolymers can show amphiphilic properties.

The most widely known small amphiphilic molecules belong to the class of surfactants. Such molecules are made up of two moieties. Hydrophilic moieties can be ionic, non-ionic, or zwitterionic. Lengths of the ionic head groups do not alter much although the sizes of non-ionic head groups can. Hydrophobic moieties are generally alkyl or alkyl-aryl chains which can be branched or linear. The length of the these chains are in the range of 8-18 carbon atoms[1].

The amphiphilic character can also be observed in fairly big molecules, polymers and block copolymers. Polymers are molecules that generally have molar mass greater than approximately 1000 g/mol. Although the boundary between polymers and oligomers is very loose the molecules below this molecular weight are referred as oligomers. Polymers having one kind of repeating monomer units are called homopolymers. Conversely, polymers that with different repeating monomer units are called copolymers or block copolymers[2]. Copolymer synthesis with different architectures, chain lengths (n, m are number of repeating units), chain ratio (n/m), and block rearrangements

are already well documented. Different architectures of block copolymers can be seen in Figure 1.1

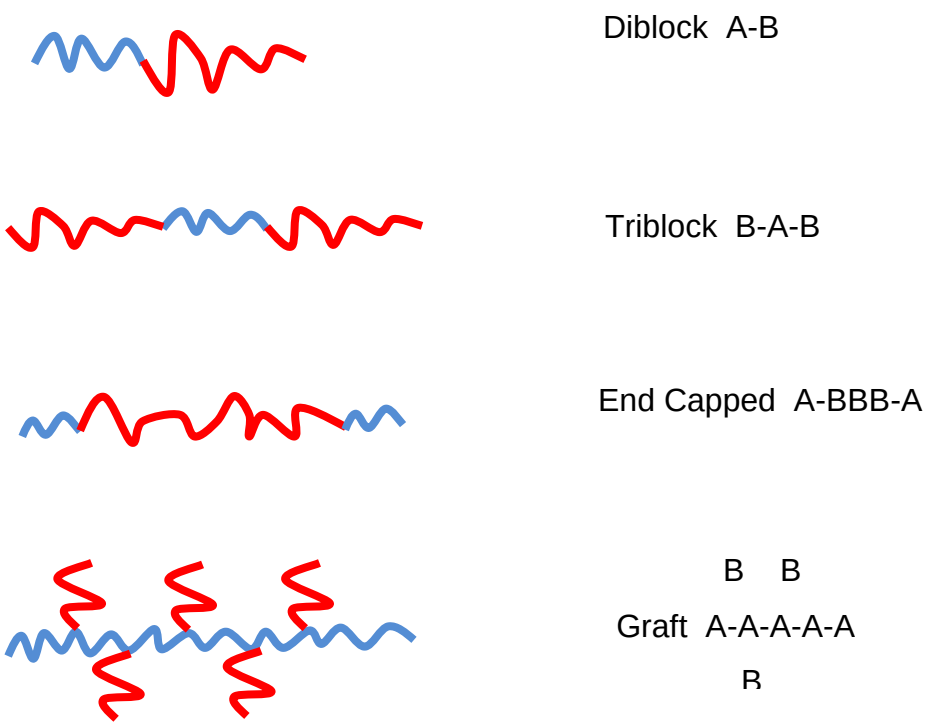
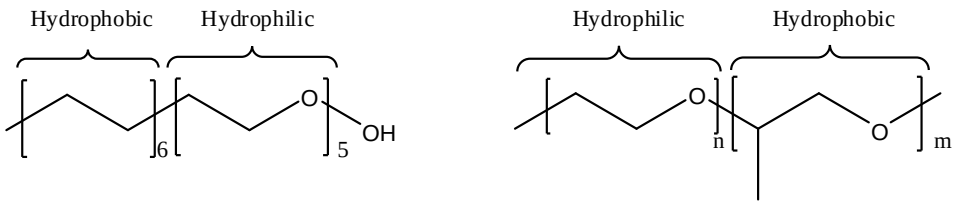


Figure 1.1 Different block copolymer architectures

One characteristic feature of surfactants is their tendency to be absorbed by the surfaces and interfaces. They are adsorbed to the interfaces in order to lower the free energy of the phase boundary. Alternatively, in water to reduce the free energy in the system they remove their hydrophobic groups from water and form aggregates which are called micelles[1]. This also holds for amphiphilic block copolymers. Like surfactants they have hydrophilic and hydrophobic parts only much bigger compared to surfactants. Like small amphiphilic molecules macromolecular surfactants similarly re-orient their hydrophobic parts to form micelles. The physicochemical so the aggregation properties of amphiphilic molecules strongly depend on the branching type of the chain, the position of

the polar group and the length of the chains. Thus, while considering aggregation of amphiphilic small molecules and block copolymers their chemical structure must be taken into account[3].

In Figure 1.2 (a) Chemical structures of a non-ionic surfactant (fatty alcohol ethoxylate) and (b) the amphiphilic block copolymer, (poly(ethylene oxide)-poly(propylene oxide) (PEO-PPO)) diblock copolymer are shown.



(a) (b)

Figure (a) 1.2 Small non-ionic surfactant, Fatty alcohol ethoxylate (b)Amphiphilic PEO-PPO diblock copolymer

Fatty alcohol ethoxylate are members of non-ionic surfactant family. They are particularly used to stabilize oil-in-water emulsions and are used in liquid and/or powder detergents as well as in a variety of other industrial applications[1]. They are generally named C_mE_n, where m is the number of carbon atoms in the alkyl chain and n is the number of oxyethylene units [1,4]. The typically have five (which is generally up to ten) oxyethylene units and C-6 alkyl chains[1]. The physicochemical properties of those ethoxylated compounds are very temperature dependent. Unlike the ionic compounds their solubility decreases with the increasing temperature[1,4–6]. After a certain temperature,

phase separation stars and this temperature is called cloud point temperature. The cloud point temperature depends on the chemical structure of the surfactant, the length of the hydrophobic alkyl chain and the number of oxyethylene units[1,4–7].

Figure 1.2 (b) shows amphiphilic PEO-PPO diblock copolymer. They consist of hydrophilic PEO and hydrophobic PPO. Like surfactants PEO-PPO copolymer is also capable of self-assembling into micelles[8–12]. Like other non-ionic surfactants their solubility decreases as the temperature increases. PEO-PPO diblock copolymers also have cloud point temperatures and all of the self-assembling properties are directly related to the number of repeating PEO and PPO units. However, most studies and applications are carried with triblock copolymers of PEO/PPO. These copolymers are known commercially as pluronics or poloxamers[8,9,11–35]. In section 1.3 PEO-PPO-PEO triblock copolymers are discussed in detail. Before triblock copolymer the properties of homopolymer of this block copolymer is discussed in section 1.2.

1.2. Poly (ethylene oxide) and Poly (propylene oxide) Homo Polymers

1.2.1. Poly (ethylene oxide)

Poly(ethylene oxide) is an hydrosoluble polymer that belongs to the polyepoxide family Figure 1.3.

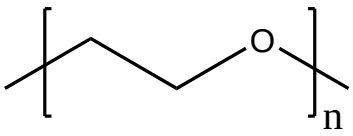


Figure 1.3 Chemical structure of oxyethylene

Polyethylene oxides can be found in various lengths. Generally the molecular weight below 3 000 g/mol are called oxyethylene (n< 68), the molecular weight up to 10 000 g/mol are called poly (ethylene glycol)'s (PEG) and bigger then this molecular weight (n> 230) they are called poly (ethylene oxide)'s[15]. Oxyethylene is an important part of non-ionic surfactant family. PEO retains complete room temperature miscibility with water at all molecular weights[34,36–63].However, unlike most of the polymers, the solubility of PEO's in water decreases with increasing temperature. Depending on the molecular weight, the aqueous solutions of PEO phase separates at a critical temperature which is called lower critical solution temperature (LCST). The critical temperatures of many polymers that are soluble in organic solvents are not sensitive to pressures up to 20 kbar[64]. Adversely, it was found[65] that increasing pressure (4 kbar) significantly lowers the LCST of PEO in water to room temperature. The reason for such unusual behavior is hydrogen bonding between PEO and water. Oxyethylene's hydrophilic (-O-) and hydrophobic (-CH_2-CH_2-) units have comparable sizes. Under ambient conditions due to H bonding of water to the chains results in extremely good solvent properties. Thus an increase at the temperature or pressure breaks the H-bonds and decreases the solvent quality[42,44,65].

The unusual behavior of PEO attracted attention because of its practical importance[38]. PEO is biocompatible and inhibits protein adsorption. These properties make PEO very popular in surface modification, drug delivery, lens coatings, drag reduction agents, and many other applications[66,67]. Also due to the simplicity of its structure, PEO represents a good model system for studying the interaction mechanism of water with biological structures. The chemical structure of the PEO is much simpler than those of proteins. It forms helical conformation in water, which constitutes a starting point to understand more complex proteins[36]. In this reason, understanding the behavior of the PEO in aqueous solutions is very important.

In water, PEO is argued to form aggregates and even though it is studied for sometime there is no unified explanation of its solubility and solvent polymer interactions.[1,36,38,55,56,68–77]. Polymer-solvent interactions depend upon the polymer structure, chemical composition, solution concentration, solvent structure, and the solution temperature[78].The following section provides an overview of these factors for PEO-water interactions through the literature on PEO clustering below LCST in the water.

1.1.1.1. Lower and Upper Critical Solution Temperature

The lower critical solution temperature (LCST) is the critical temperature above which the components of a mixture are not miscible. In contrast, the upper critical solution temperature (UCST) is the critical temperature below which the components of a mixture are immiscible for all compositions. These two boundaries may exist in one polymer-solvent system which is the case for PEO-water. Water is a good solvent for PEO at low temperatures and water approaches theta solvent for PEO with increasing temperature[78,79]. Even though PEO retains soluble in water upon heating at ambient pressure[80], temperature increases above 100 ^{o}C results in phase separation. Further heating solubilizes the PEO again. The phase diagram of the binary mixture PEO/water represents a “closed loop” coexistence type that showing both a LCST and a UCST as shown in Figure 1.4[34,81].

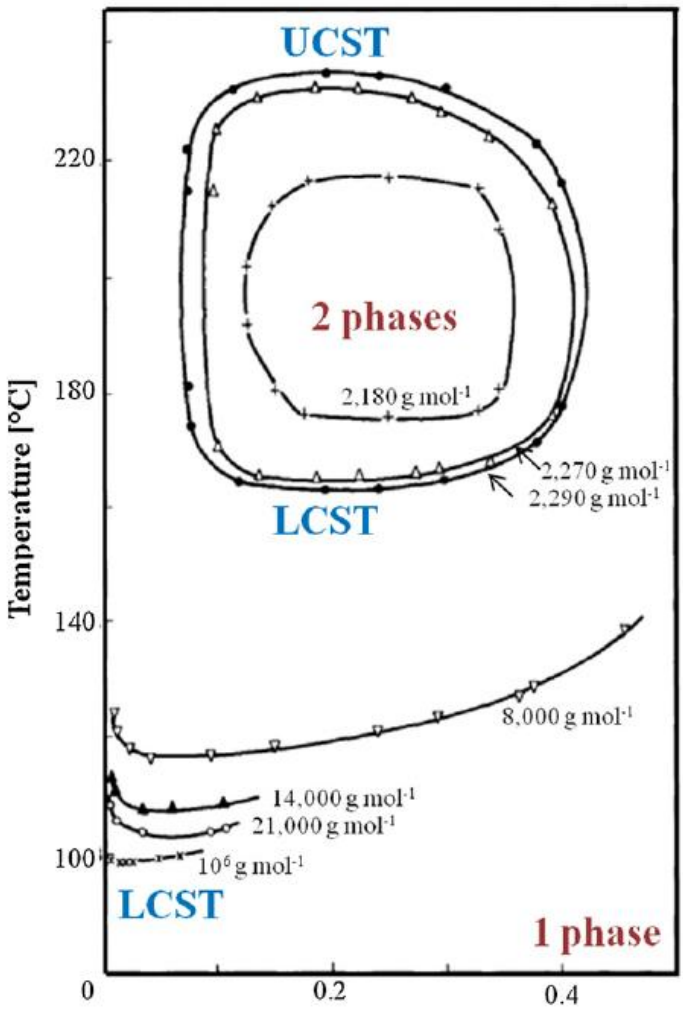


Figure 1.4 Temperature/Weight Fraction LCST and UCST dependence versus M_w[34,81]

In Figure 1.4 solution temperature is drawn as a function of polymer weight fraction. Open circle and closed triangle represent the critical solution temperature of polymer-water binary systems and the curves are fits to these points. They represent the coexistence curve. High molecular weight PEO's show only LCST type of behavior. Above this curve PEO-water homogenous solution shows phase separation. The closed loop type phase behavior is observed under molecular weights of 2.290 g/mol, which contains both LSCT

and UCST together. In this type of phase behavior, polymer is miscible out of the loop and insoluble inside.

Increasing molecular weight (M_w) reduces the solubility of the PEO in water resulting in lower LCST but higher UCST[81]. This behavior is created when hydrogen bonds that are formed between PEO chains and water are supposed to enhance the structuring of solvent molecules around the polymer chain. Even though this is entropically unfavorable (favorable enthalpy term is dominant at low temperatures) it results in PEO miscibility. On the contrary, the entropy contribution becomes predominant at higher temperatures causing a disruption of the water structure around the PEO, which leads to a phase separation[81]. More favorable interactions at longer chains more solvent networks are formed and with increasing temperatures they easily phase separate. However above 50 000 g/mol M_w and 0.3 % polymer weight percent LCST behavior becomes insensitive to M_w and concentration.[82]

Keeping low molecular weight PEO-water solutions in between lower and upper critical temperatures leads system to phase separation which results in aggregation. Also in some studies it has been shown that PEO aggregates below LCST[38,40–49,51–55,61,62,83] which will be discussed in the next section.

1.1.1.2. PEO Clustering in Aqueous Solutions: Temperature Effect

The PEO's behavior in water below lower critical solution temperature has been studied for years in literature. The possible clustering below LCST upon temperature change has been investigated using different techniques in many studies[45,55,56,70,74,77,78,84]. It must be noted that in all these studies the polymer concentration in water is different. The effect of concentration will be

discussed in the next part. According to these studies increase in solution temperature either results in relatively big aggregates or decreased size of single molecule chains[45,55,56,70,74,77,78,84]. In Mehrdad *et al*'s study, on the intrinsic viscosities of low molecular weight PEO (20 000 g mol^{-1}) in water, it was stated that intrinsic viscosities of PEO are decreased in pure water, with increasing temperature[78]. It is proposed that this increase in temperature results in change of segment-segment and segment-solvent interactions. The interaction of segment-segment is favored instead of segment-solvent by the increasing temperature; therefore, PEO chain shrinks, and the end-to-end distance becomes smaller. This theory is supported by small-angle neutron scattering (SANS) studies and supported by other studies, chains of single molecules shrinks with increasing temperature [37,43,53,56,63,73,77].

In addition to these studies the aggregation of PEO in water has also been well studied[36,41–45,47,48,52–56,69,70,77,85]. After such studies it has been proposed that the oxygen/ethylene repulsive interactions get stronger and ethylene/ethylene attractive interactions get stronger with decreasing temperature. For example clustering is favored in aqueous 3 % PEO (M_w =96 000 g/mol) solution temperatures below 50 ^oC [69]. Since ethylene groups like each other, they tend to stick together everytime they get closer. Monomers repel each other in good solvent conditions. Inversely, they form clusters at elevated temperatures[69]. This proposition is also consistent with Smith *et al*'s study on temperature dependence of PEO-water[74].However, the discussion on the temperatures dependence of aqueous PEO's clustering is not concluded since there are other many studies suggesting PEO does not form clusters in water with increasing temperature below LCST[36,37,39,46,51].

1.1.1.3. PEO Clustering in Aqueous Solutions: Concentration Effect

Molecular interactions of PEO-water have been found to be affected by their concentration[44,68,75,77,84,86]. In these studies it is suggested that clustering tendency increases with increasing PEO concentration in water. One of the recent studies[68] summarizes experimental results using viscoelastic parameters is shown in Figure 1.5.

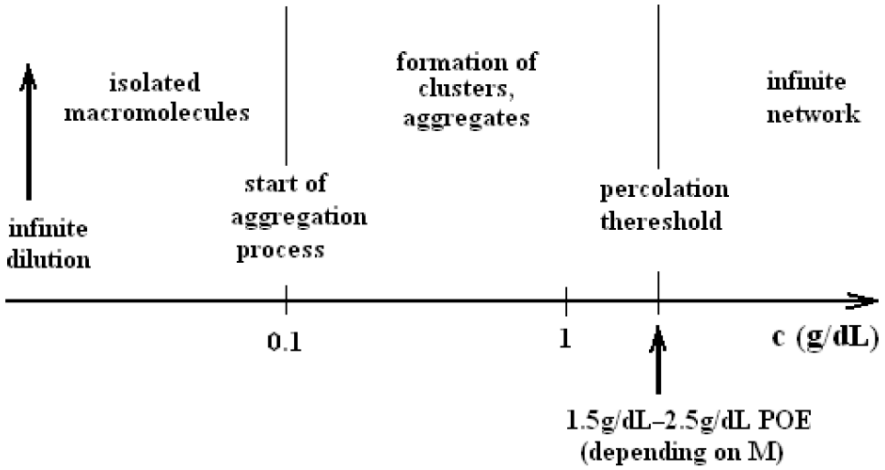


Figure 1.5 Aggregation points and corresponding concentrations[68]

At very low concentrations (c < 0.1 g/dL), most of the macromolecular chains are isolated; some of them can be closed to loops, or present in small aggregates (less than 2 % chains). The aggregation process suggested to start at concentrations above 0.1 g/dL [68]. There are four types of hydrogen bonding these are water-PEO, water-water, PEO-water, and PEO-PEO. PEO-PEO hydrogen bonding is the weakest among the four and this dominates only at high polymer concentration. PEO- water hydrogen bonding is the strongest. It decreases only at high polymer concentration due to competition with PEO-

PEO hydrogen bond formation[38,76]. As concentration increases clusters are formed resulting in PEO network formation.

1.1.1.4. PEO Clustering in Aqueous Solutions: Chain End Effect

One other fundamental factor to understand the PEO- water interactions is hydrogen bonding [38,44,68,71,75,76,79,87]. Not only hydrogens of water act as proton donors, but there are other types of hydrogen bonding that also depend on the PEO end groups. Figure 1.6 shows possible end group configurations for PEO[38].

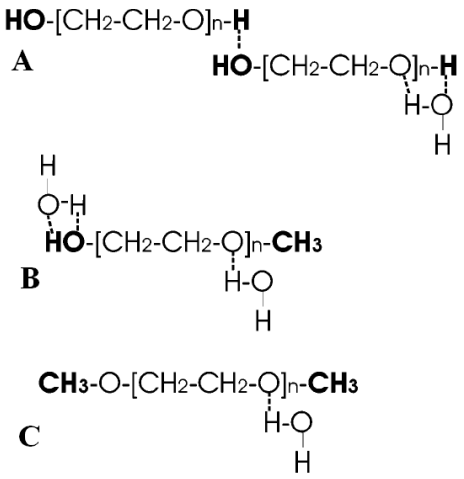


Figure 1.6 PEO's having different chain ends[38]

The most of the commercially available PEOs are the ones that are terminated by $–CH_3$ groups at both ends. In addition to this two –OH or one –OH one $–CH_3$ chain terminators are also present. For hydroxy terminated PEO, there is an extra proton source of providing two additional types of hydrogen bonding: PEO-water and PEO-PEO. These two types of hydrogen bonding

compete with each other and with water- PEO and water -water hydrogen bonding. The additional source for hydrogen bonding between PEO and water via end groups, shown to improve the overall hydration of PEO chains. It affects solubility and other properties of PEO[38,76].

In general, end groups increase the overall hydration and enhance the possibility of physical crosslinking among PEO molecules. Polymer hydration is characterized by the hydration number. The hydration number is the number of hydrogen bonded water molecules per repeating unit. This number decreases with increased temperature and polymer concentration. Comparison of different polymer concentrations and temperatures shows that the contribution of the end group to the hydration becomes important especially in the poor hydration regions such as high polymer concentration, low water content, and high temperature and short chain lengths. For example for methyl-terminated PEO, the only possible mechanism of PEO cross-linking is via water. Thus, termination of PEO by one hydroxyl group improves the solubility of PEO chains [38 76].

These findings are consistent with other reports using different end groups in solutions. Hydroxy end capped PEO chains do not form clusters in water due to chain-end effect. However–CH_3 terminated PEO chains form clusters in water. Overall it is found that end group clustering is, not the dominant form of clustering[69–71]In general the boundary between poly (ethylene glycol), where end-effects can be noticeable, and poly (ethylene oxide), where the influence of end groups is minor, is between 3350 and 10000 g/mol. So the effect of the end groups on phase behavior of PEO remain noticeable for PEO chain up to 500 repeating units long.[38]

1.1.1.5. PEO Clustering in Aqueous Solutions: Salt Effect

The influence of inorganic salts on solvent properties for aqueous PEO solutions is a known phenomenon since 1950s [82,88]. The presence of such salts, or rather salt ions, in solution disturbs the hydrogen bonding and the ordered water structure along the PEO chains. Bailey *et al.* have reported that the intrinsic viscosity of PEO in salt solutions is lower than that in pure water solution under comparable conditions. This suggests that the polymer chains are more contracted in the salt solutions[82]. Commonly accepted effects of salts are given at figure 4 [81,82,89]

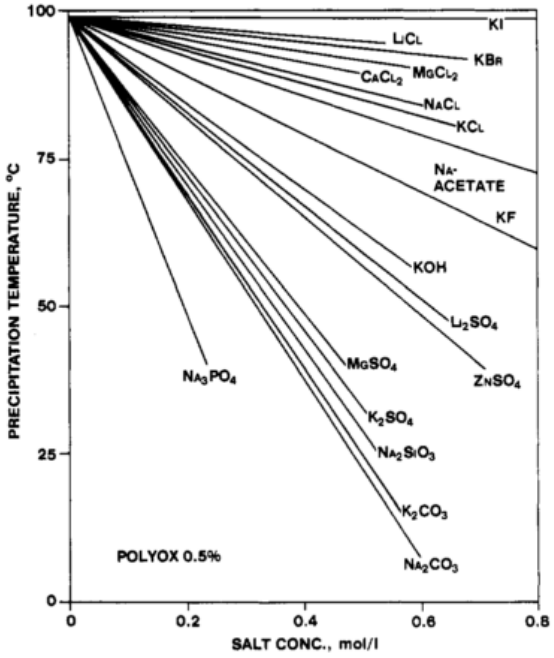


Figure 1.7 Effect of salt type and concentration on precipitation temperature of 0.5 weight % PEO aqueous solution[89]

In Fig. 1.7 the precipitation temperature of the PEO aqueous solutions are presented as a function of salt type and concentration. Inorganic salts containing anions that have high hydration, or high water structure making tendency form aqueous-two-phase systems with low molecular weight PEO. Lithium and multivalent cations reduce the tendency of the salt to form a two-phase system, because of their interactions with the ether oxygens of PEO. Among various Na salts, the higher the valency of the anion, the lower the concentration required for phase formation. The higher the temperature, the lower the amount of salt required for phase formation.

1.2.2. PPO

Early studies on the phase behavior of poly (propylene oxide) are made by Malcolm and Rowlinson[90,91]. PPO is an polyether that has an closely related structure to PEO. Compared to PEO it has one more additional carbon atom at its repeating unit. This addition of atoms results in increased hydrophobicity. Below the boiling point of the solvent under ambient pressure this increased hydrophobicity, decreases the phase transition temperature of the polymer-water mixture. The LCST of PEO having molar mass of 400 g/mol is known to be above 100 ^{o}C[34], whereas PPO having molar mass of M_w 400 g/mol is found to be 50 ^{o}C[90]. Further studies made on PPO to determine its LCST temperature as a function of concentration and molecular weight[91]. These studies showed that like PEO, as the molecular weight of PPO increases the LCST's decreases.

1.3. PEO-PPO-PEO triblock Copolymers

Pluronic or poloxamer is commercial name of high molecular weight triblock copolymer made up of repeating monomer units of two kinds. Triblock copolymers of poly (ethylene oxide) - poly (propylene oxide) - poly (ethylene

oxide) (**PEO**)- (**PPO**)- (**PEO**) are amphiphilic molecules. The PEO is hydrophilic and PPO is hydrophobic part of the molecule Figure 1.8.

Figure 1.8 PEO-PPO-PEO Triblock copolymer

Pluronics are both surface active and are capable of micelle formation in aqueous solutions. The interest in these surfactants is due to their micellization capabilities. This property allows them to be used as micro containers for hydrophobic solutes[92]. Hence they are used in many industrial applications such as detergency, dispersion, stabilization, foaming, emulsification, lubrication[93]. They are widely used in pharmaceutical industry due to these thermoreversible properties. The pluronic micelles are widely used in drug delivery since they are capable of carrying water insoluble drugs. In addition to being able to form stable micelles, they are found to be highly compatibile with drug candidates having diverse nature and ingredients in formulations. Their specific applications in cancer, gene therapy and other areas have well documented[33,93,94,95]. The particular interests in pluronics for pharmaceutical and biomedical applications are due to the following reasons. PEO is a biocompatible polymer. By attaching hydrophilic PEO chains to PPO, the advantage of PEO's biocompatibility preserved while the phase transition temperature is lowered due to the hydrophobicity of the PPO backbone. Water solubility of PPO solutions temperature dependence was described previously (sec 1.2.2.)The combination of PEO and PPO in a single molecule creates molecules with amphiphilic character, which depend critically on both molecular architecture, and thermodynamic parameters like temperature and pressure. With this reason, these polymers can form various structures such as spherical, rod-like, and pancake-shaped micelles, and complex-structured fluids like the bicontinuous L_3 microemulsiones[94]

1.4. Self-Assembly of Amphiphilic Block Copolymers in Solution

Self-assembly is the spontaneous reversible organization of components into ordered structures without any external driving force. These highly stable ordered structures hold together by weak intermolecular forces such as van der Waals, hydrophobic, hydrogen-bonding and screened electrostatic interactions and water-mediated hydrogen bonds[96]. Self-assembly process is important in both scientific research and industrial applications since in solutions it plays a key role for the optimization of design and processing conditions.

The type of assembly depends on the amphiphile's structure, concentration, temperature and pressure[97]. At very low concentration the amphiphile forms a monolayer at the water-air interface. Above a certain concentration amphiphiles self-assembles into different structures, such as rods, discs, spheres, bilayers and vesicles. At much higher concentrations they form diverse liquid-crystaline phases, such as, bilayer stacks and hexagonal phases[1,15,97]. The shape and sizes of these assemblies are determined by the two opposing forces. These forces are mainly act at the interface between the surfactants and water. First of these forces, is the attractive interactions between the monomers. This is due to hydrophobic effect (Section 1.5), it makes molecules associate. The second one is the repulsive interactions. This interaction is a result of electrostatic and/ or repulsive interactions between the hydrophilic head groups. This repulsion makes head groups stay in contact with water. At a given set of conditions (temperature, concentration, pressure, pH) balance between these two forces determines the shape of the assemblies.

The Figure 1.9 shows the general sequence of self-assembly structures upon change of temperature and polyoxyethylene chain length for polyoxyethylene-based surfactants.

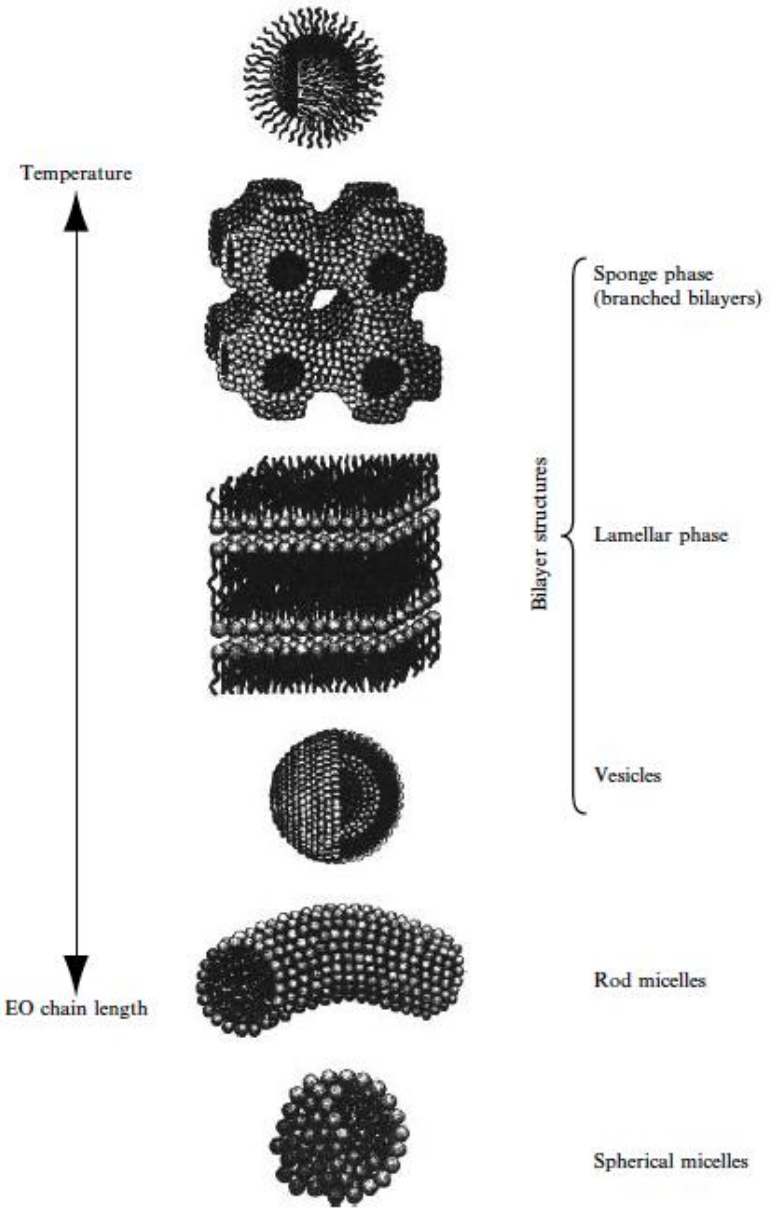


Figure 1.9 The self-assembly structures of polyoxyethylene-based surfactants upon change in temperature and polyoxyethylene chain length[1].

In this case the temperature and polyoxyethylene chain length have opposing effects. As polyoxyethylene chain length increases above the critical aggregation concentration in order to minimize the polar head group repulsion

spherical micelles forms. Vice versa, as temperature increase the hydrophobic effects dominates and reversed micelles, non-polar tails that are directed to water, form.

1.5. Hydrogen Bond and Hydrophobic Effect

Water has unexpected properties due to hydrogen bonding. Despite being a small molecule, it has high melting and boiling points which is not an inherent property of molecules lacking strong columbic or metallic bonds or other intermolecular forces. These properties are the result of strong and orientation-dependent hydrogen bonds. The hydrogen bonding and hydrophobic effect are very important in nature. It is the reason for the formation of lipid membranes and affects many other biological processes like protein folding. In soft matter it plays a role in many systems.For example it is the driving force for amphiphilic self- assembly.

The driving force for amphiphilic self-assembling systems is the so-called hydrophobic effect in water. The main reason is entropic and is due to the unique peoperties of the water molecules. When a non-polar molecule (e.g. an alkane) is placed in water the water molecules around it create a cavity to accommodate it. Since alkane molecules cannot form hydrogen bonds with water the cavity must be formed by either breaking hydrogen bonds, or by rearranging the water molecules. The tetrahedral shape of water molecules allow them to arrange themselves without breaking hydrogen bonds. However, during this process the water molecules become more ordered than its initial state. Such an order decreases the entropy of the sytem . If the size of hydrophobic parts (PPO for PEO-PPO-PEO triblock copolymer) that are present in water is above a certain size, the loss of entropy becomes too much for water . Instead, more favorably water breaks hydrogen bonds and creates larger cavities to accommodate them. This leads to an effective attraction

between the PPO molecules which is called hydrophobic interaction. Due to the hydrophobic interaction, the PPO molecules have stronger mutual attraction in water than they do in free space. Thus PPO forms a central hydrophobic core where in methyl groups interact via van der waals forces with water to solubilize. Meanwhile, the water solubility of the molecule is achived by PEO blocks through hydrogen bonding to ether oxygen of the molecule. Thus pluronics when they are dispersed in the water at low concentrations and low temperatures, exist individually as mono molecules. Their PPO part is mostly covered with water soluable PEO parts so that they can form hydrogen bonds with water. However as the concentration of the pluronic in the system increases PPO's come together and form multimolecular aggregates resulting in micelles with PPO block in the core and PEO in the corona.

1.6. Factors Affecting the Critical Micellization Temperature of PEO-PPO-PEO triblock copolymer

1.6.1. Concentration Effect

The T_{cm} of for both triblock copolymers decrease as the polymer concentration increases[98–100]. The solubility of these polymers decreases as the temperature increases. The decrease in the solubility results in much favored micelle formation due to increased hydrophobic interactions. When the polymer concentration is higher there are more hydrophobic units in the environment to form micelles. The collision probability of the polymers increases with the increasing concentration so, higher polymer concentration results in lower T_{cm}.

1.6.2. Hydrophilic / Hydrophobic Ratio Effect

Increase in the PEO/PPO ratio in triblock copolymer causes increase in T_{cm}[23,99]. Polymers hydration is increased with the increase PEO. This result in increase in the polymer solubility. For more hydrophilic copolymers ΔH^o change in between 182-130 kj/mol[28]. In contrast for polymers having higher hydrophobic blocks ΔH^o is in the order of 300-350 kj/mol[28]. Decrease in the unfavorable contribution of ΔH^o_{mic} with increasing PEO content result in much negative ΔG^o.

1.6.3. Salt Effect

In the presence of salts the unimer to micellization transition temperatures are explained[22] by three kinds of interactions. First two effects are interfacial tension and entropy effect. It is found that these mechanisms alter the critical micellization temperature transitions linearly. Whereas, direct binding of anions does not effect the transitions linearly due to saturation.

First, the hydrophobic hydration of the PPO and PEO block can be affected by both different type and concentration of anions. It is known that when a hydrophobic solute is small enough, water forms water cages around instead of bonding it. This hydrophobic hydration results in formation of cavities where the water and polymer meet to form an interface[1,97,101]. The free energy to create this cavity is directly proportional to the interfacial tension. This interfacial tension changes in the presence of salts. The increase in interfacial tension, free energy of cavity formation, decreases the solubility of PEO-PPO-PEO. Thus, when the concentration of such anion is increased in the system transition temperature drops. If the free energy of cavity formation is reduced, solubility of PEO-PPO-PEO increases. The critical micellization temperature increases[1,97] as the salt concentration increases.

Second, anions can interact with polymer through changing the entropy of the surrounding water. In case of PEO-PPO-PEO, water interacts with the oxygen in the polymer chain, hydrophilic portion, and form a hydration layer. When a kosmotropic anion is present the interaction of water with the polymer will be reduced and this results in reduced solubility of the polymer (decreased the critical micellization temperature). In contrast, when a chaotropic anion is present it will not affect the structuring of water as dramatically as in the case of kosmotropes. Thus the critical micellization temperature will increase however the effect will be less. Disruption of the structuring affects the entropy of the micellization process.

Final suggested way for salts to interact with polymer and alter their critical micellization temperature is directly binding to polymer. This direct binding is through hydrophobic moieties of the polymer[22]. This is especially possible when salt is poorly hydrated. In this case it can shed its hydration water and bind to the hydrophobic portion of the polymer easily.

2. Materials and Method

2.1. Chemicals

Polymers used in this study given in Table2.1 and Table 2.2.

Table 2.1

Polymer	M_w (g/mol)	Company
PEO	2 000	Merck
	10 000	Merck
	100 000	Aldrich
	200 000	Aldrich
	400 000	Aldrich

Table 2.2 Different Pluronics Marketed by Sigma Corporation

Pluronic	F 68	F 127
Poloxamer	188	407
PEO repeating number	80	101
PPO repeating number	27	56
Ethylene oxide content (%)	79.9-83.7	71.5-74.9
Molecular Weight	7680-9510	9840-14600
Physical Form (RT)	Solid	Solid
Cloud Point (10%) ^{o}C	>100	>100

HPLC grade water used in experiments and was purchased from Merck. Analytical grade sodium carbonate (Na_2CO_3), sodium chloride (NaCl), sodium acetate (CH_3COONa) was purchased from Merck. Two other analytical grade sodium salts, sodium iodate (NaI) and sodium thiocyanate (NaSCN), were purchased from Aldrich.

2.2. Instruments

2.2.1. Dynamic Light Scattering (DLS)

Diameters of particles are measured by dynamic light scattering technique. The surrounding of the particle in a liquid medium affects the movement of the particle. Particles are bombarded by the solvent. It is called as Brownian motion theory. According to this theory bigger particles move slowly

and small particles move quickly since small particles can be kicked by solvent easily. If light hit a small particle the particle scatters light in all directions. When a screen is held close to the particle, the screen is illuminated by the scattered light. Such screen would show a speckle pattern as shown in Figure 2.1.

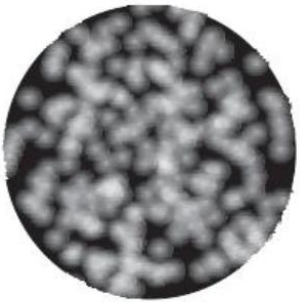


Figure 2.1 Speckle pattern of screen consists of dark and bright areas[102]

The scattered light represented by the bright areas is constructive interference and by the dark areas is destructive interference.

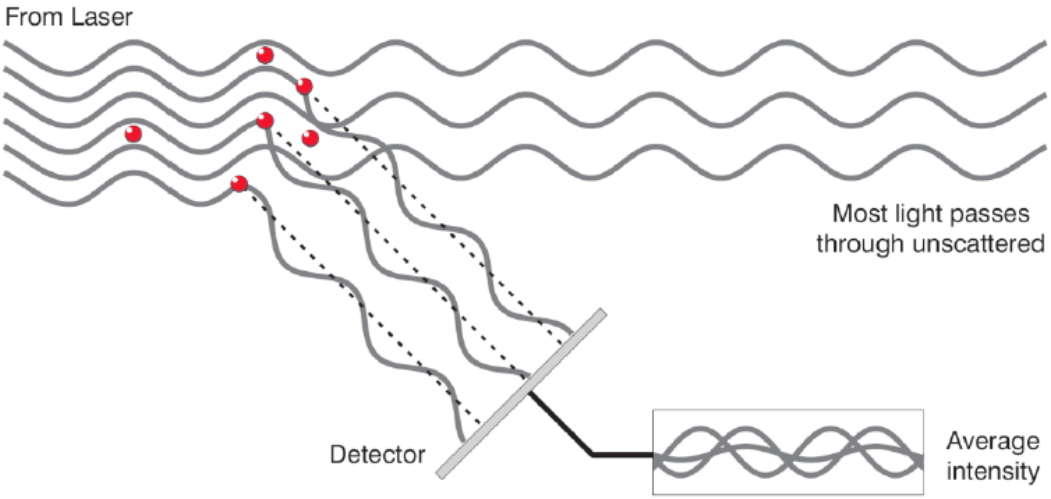


Figure 2.2 Representation of propagated waves when the light interacts with the particles[102]

The propagated waves after the interaction of light with the particle are represented in Figure 2.2. If the particles move around the scattered light the intensity of light fluctuate because of the diffusion. Diffusion coefficient (D) is the intensity of light in time. Diffusion coefficient can be calculated using Stokes-Einstein relation[103]

$$D=\frac{k_B T}{6\pi\eta a}$$

Equation 2.1

where k_B is the Boltzman constant, T is the temperature η is the viscosity of the medium and a is the diameter of the particles. The similarity between two different signals in a period of time is measured with a digital correlator examining the fluctuation in scattered intensity. If the change in the position of the particle is not significant the correlation is high at short time intervals. If the correlation decays exponentially and then reaches zero that means delay in time is longer.

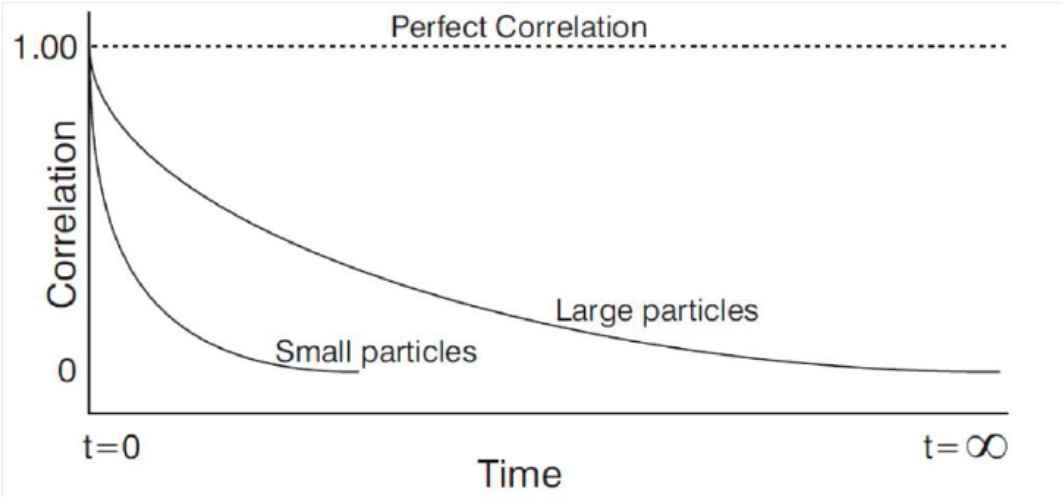


Figure 2.3 Correlation function against time for small and large particles[102]

Figure 2.3 shows the correlation function for large and small particles. The correlation function decays much faster for small particles since the diffusion is faster for small particles then big particles. The rate of the correlation function analyzed through autocorrelation function is also related with the particle size. The second order curve is generated from the intensity trace is:

$$\mathbf{g^2(q;\tau)} = \frac{\langle \boldsymbol{I(t)I(t+\tau)} \rangle}{\langle \boldsymbol{I(t)} \rangle^2}$$

Equation 2.2

Where $g^2(q; \tau)$, is the autocorrelation function, q is the wave vector, τ is delay time and I is the intensity The decay is a single exponential for monodisperse samples. The relation of the second-order autocorrelation function with the first-order autocorrelation function is given by The Siegert equation;

$$\mathbf{g^2}(\boldsymbol{q};\boldsymbol{\tau}) = \mathbf{1} + \boldsymbol{\beta}[\mathbf{g^1}(\boldsymbol{q};\boldsymbol{\tau})]^2$$

Equation 2.3

Where β is the correction factor that change with the geometry and the alignment of the laser beam in the set-up. After the first autocorrelation function is formed different approximation can be used to determine size of particles. Equation 4. is the simplest way to treat monodisperse population function as a single exponential decay;

$$\mathbf{g^1}(\boldsymbol{q};\boldsymbol{\tau}) = \mathbf{exp}(-\boldsymbol{\Gamma}.\boldsymbol{\tau})$$

Equation 2.4

where Γ is the decay rate. The diffusion coefficient D_t can be derived with the wave vector q.

$$\boldsymbol{\Gamma = q^2 D_t} \quad \textbf{where} \quad \boldsymbol{q = \frac{4\pi n_0}{\lambda} \sin\left(\frac{\theta}{2}\right)}$$

Equation 2.5

where λ, is the incident laser wavelength, n_0 is the refractive indices of the sample and θ is angle with the detector and sample cell. The software of the DLS uses decay rate algorithms and extracts the different size classes to produce an intensity distribution graph as shown in Figure 2.4.

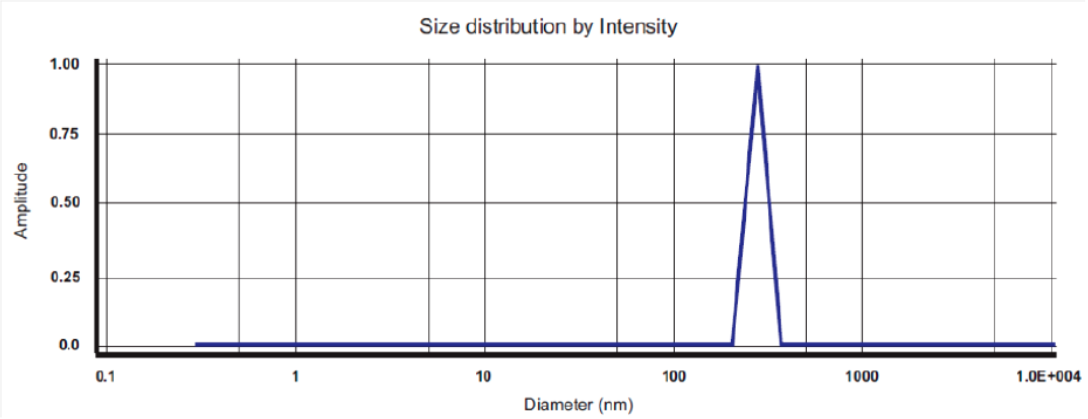


Figure 2.4 Typical intensity distribution graph[102]

The x axis shows a distribution of size and y axis represents the relative intensity of the scattered light. Maxima of the curve can be used as an average size of the particles. The DLS used in this thesis is Malvern Zetasizer Nano S DLS. Laser source is 633 nm red laser. It illuminates the solution and a detector measures the intensity of the scattered light at an angle of 173° [102]This is known as backscatter detection. In this angle the incident beam does not have to travel through the entire sample and reduces multiple scattering. The light will pass through a shorter path length which allows measurements of concentrated

samples. Contaminants such as dust particles are larger compared to sample size. Since larger particles mainly scatter in forward direction, backscatter detection also reduces the effect of contaminants on measurements.

2.2.2. Optical Microscopy

MTI Corporation, MM500T Advanced Metallurgical Microscope was used to observe self-assembled PEO-PPO-PEO fibers formed in aqueous solutions. The samples were prepared by solvent casting. To capture the image from the optical microscope MTI Corporation, DCM-310, 3MP Hi-speed Universal digital camera head is used.The samples prepared by stacking. The aggregates are placed between lams substrates without drying from their solutions.

2.2.3. Scanning Electron Microscopy (SEM)

Morphology of self-assembled fibers are examined with the help of scanning electron microscope (Zeis EVO LS15). The advantages of SEM are providing morphological properties of fibers and thickness information of the fibers which are not provided by light microscope. SEM working mechanism is basically scanning the specimen with an extremely small focused of electrons (a few nm in diameter). The image is produced by signals coming from the high energy electron bombardment on the sample. The intensity differences of the collected signals produce images. The brightness modulation and the depth of field adjustment help to get better picture of the specimen.

2.3. Experimental Details

All polymer-water solutions were prepared by dissolving polymer in water through orbital shaking. Salt containing solutions were prepared similarly. Before DLS measurements all solutions kept 24h in room temperature to obtain homogenous solutions.

The size of single molecule chains and possible aggregation PEO chain were determined in aqueous solutions by DLS as a function of temperature. Temperature was increased from 15 to 65 ^{o}C by 1 ^{o}C steps. At each temperature 100 DLS measurements were taken at 15 s duration time. The sample was equilibrated for 3 min at each temperature before each measurement.

DLS was used to determine critical micellization temperatures of poly (ethylene oxide)-poly (propylene oxide)-poly (ethylene oxide) aqueous block copolymer solutions. Critical micellization temperature was determined for different polymer concentrations and in the presence of a series of sodium salts. At each temperature 100 DLS measurements were taken at 15 s duration time. Temperature was increased from 15^{o}C to 75^{o}C by 1 ^{o}C steps. The sample was equilibrated for 3 min at each temperature before each measurement.

3. Results and Discussion

The self-assembly of PEO-PPO-PEO triblock copolymers in aqueous solutions has been investigated in this study. Self-assembled fiberlike aggregates of PEO-PPO-PEO were observed for the first time below the critical micellization temperature which was quite unexpected.

As described in Chapter 1, temperature-concentration phase diagram of micellar structures in aqueous PEO-PPO-PEO solutions has long been studied and is well-known. Lower critical solution temperature of aqueous PEO solutions is above 100 ^{o}C and that of aqueous PPO solutions is 50 ^{o}C[90]. Therefore, PEO-PPO-PEO triblock copolymers are soluble at room temperature. When triblock copolymer concentration is above the critical micellization concentration (CMC), as temperature is increased, spherical micelles form with insoluble PPO at the core and soluble hydrated PEO at the corona. As PEO-PPO-PEO concentration and temperature are increased further, other micellar structures and gels are also observed.

Insoluble self-assembled fiberlike aggregates were observed when 1 mg/mL (0.1 weight %) aqueous PEO-PPO-PEO solutions were kept below T_{cm} (at 25 ^{o}C) for extended times (on the order of days). To differentiate between fiber formation by self-assembly and micellization, we have investigated the T_{cm} of aqueous PEO-PPO-PEO solutions as a function of salt concentration. By adding various sodium salts, T_{cm} was changed and the observation of self-assembly into fibers below T_{cm} was confirmed.

To understand the driving force for the formation of self-assembled aggregates, we have investigated aqueous PEO solutions as a function of temperature between 15-65 ^{o}C. As discussed in Chapter 1, although PEO is

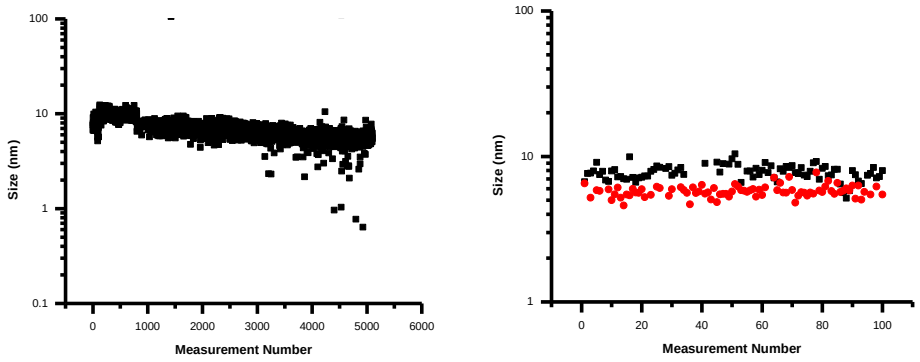
completely soluble in water, PEO clusters have long been observed in aqueous solutions, especially at elevated temperatures.

This chapter is organized as follows: Investigations of the sizes of PEO chains at different molecular weights as a function of temperature are presented in Section 3.1. Section 3.2 focuses on the investigation of the micellization of two different PEO-PPO-PEO triblock copolymers. The dependence of T_{cm} on the concentration of various salts is presented. In Section 3.3, self-assembled fiberlike aggregates are presented as observed by microscopic investigations. Possible structures for the observed fiberlike aggregates and the driving mechanisms for such self-assembly are discussed.

3.1. PEO in Aqueous Solutions

3.1.1. Size of a PEO Chain in Aqueous Solution

Figure 3.1a shows the DLS data of 1 mg/mL PEO-10K solution. There are total of 5100 data points taken in the direction of increasing temperature from 15 ^{o}C to 65 ^{o}C. In the Figure 3.1.a the first 100 data points correspond to 15 ^{o}C, the second 100 to 16 ^{o}C and so. Fig. 3.1b shows the distribution of the data that were presented in Fig. 3.1a taken at 15 ^{o}C (squares) and 65 ^{o}C (circles).



(a) (b)

Figure 3.1 Raw DLS data of Aqueous PEO 10k solution having 1 mg/ml Concentration (a) Each data point represents the R_h of single PEO 10k chain in water and each 100 set of measurements corresponds to 1 ^{o}C. First 100 measurements represents data at T= 15^{o}C. Data 100-200 T= 16 ^{o} C and so on. (b) the black squares represents the data taken for T=15 ^{o}C and red circles represents data taken for T= 65 ^{o}C

A decrease in size with increasing temperature is clearly evident in Figure. 3.1a. This is more easily observable in Figure 3.1.b shows the 100 data points taken at T=15 ^{o}C and T = 65 ^{o}C. At each temperature, the measured size was constant with a Gaussian distribution.

The sizes of PEO 10k unimers were found using 100 measurements. The Figure 3.2., shows the distribution of PEO 10k unimer sizes at T=15 ^{o}C.

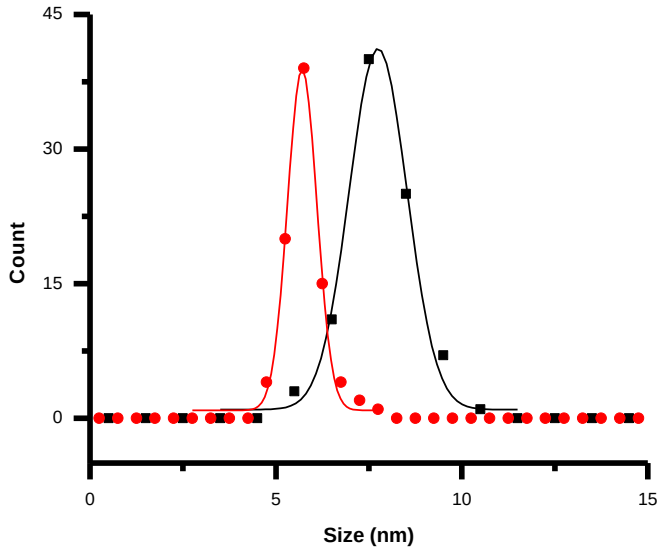


Figure 3.2 Distribution of the 15^{o}C and 65 ^{o}C data of Fig 3.1. b. Black squares are for T= 15 ^{o}C and red circles are for T= 65^{o}C. The solid lines are Gaussian fit to the data.

The solid lines are Gaussian fits to the size distributions. The size corresponding to the peak value of the Gaussian fit, xc, gives the average size of the polymer chains. The width of the Gaussian fit, w, corresponds to twice the standard deviation, σ. As seen clearly in Fig. 3.2, the average size of PEO-10K chain decreases from 7.74 nm at 15 ^{o}C to 5.70 nm at 65 ^{o}C. The distribution of sizes also gets narrower with increasing temperature: σ is 0.78 nm at 15 ^{o}C and 0.40 nm at 65 ^{o}C.

The size determined by DLS corresponds to the hydrodynamic radius of the polymer chains (R_h). R_h was converted to the radius of gyration of the polymer chains (R_g) using Equation 3.1[104] to compare with the theoretical R_g predictions;

$$R_g \approx 0.77 \times R_h$$

Equation 3.1

3.1.2. The Dependence of R_g of PEO chains in Aqueous Solutions on Temperature

The average size of PEO chains in aqueous solutions was determined as a function of temperature for 5 different molecular weights (M_w). PEO solution concentrations was set to 0.1 wt%. Figure 3.3. shows the log-log plot of radius of gyration (R_g) of a single PEO chain as a function of molecular weight at 25 ^oC.

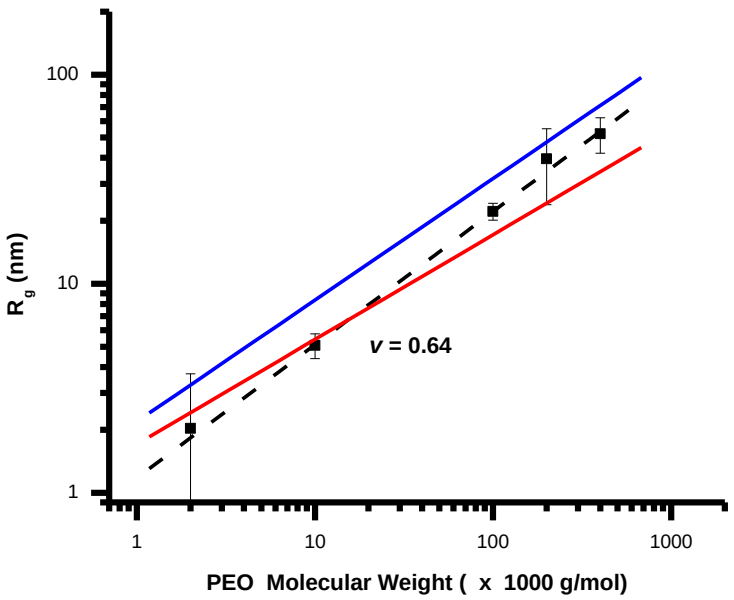


Figure 3.3 The black data points are R_g's of PEO's plotted as a function of molecular weights at T = 25°C. Black dashed line is linear fit to data points. Blue line represents the theoretical good solvent boundary whereas red represents theoretical theta solvent boundary.

The solid line is a linear fit to log R_g vs log M_w and has a slope of 0.64. This indicates that $R_g \approx N^{0.64}$. According to Flory theory[105], the exponent *v* is 0.50 for a theta solvent and 0.58 for a good solvent. The experimentally determined value of *v*= 0.64 at 25°C indicates that water is a good solvent for PEO at 25 °C as expected. The solid lines in Figure. 3.3 represents the theoretical Rg values for theta solvent (red, lower line, *v* = 0.50) and good solvent (blue, upper line, *v* = 0.58). Theoretical R_g values were calculated using Eqn. 3.2 and taking the PEO monomer size a = 0.18 nm[51,56].

$$R_g = a \times N^{v}$$

Equation 3.2

At a certain temperature, as the molecular weight of the PEO increases, Rg increases. This is expected since molecular weight is proportional to the logarithm of the number of monomers, N, according to Equation 3.2. Figure 3.4. shows the log-log plot of R_g of a single PEO chain as a function of molecular weight at 60 °C.

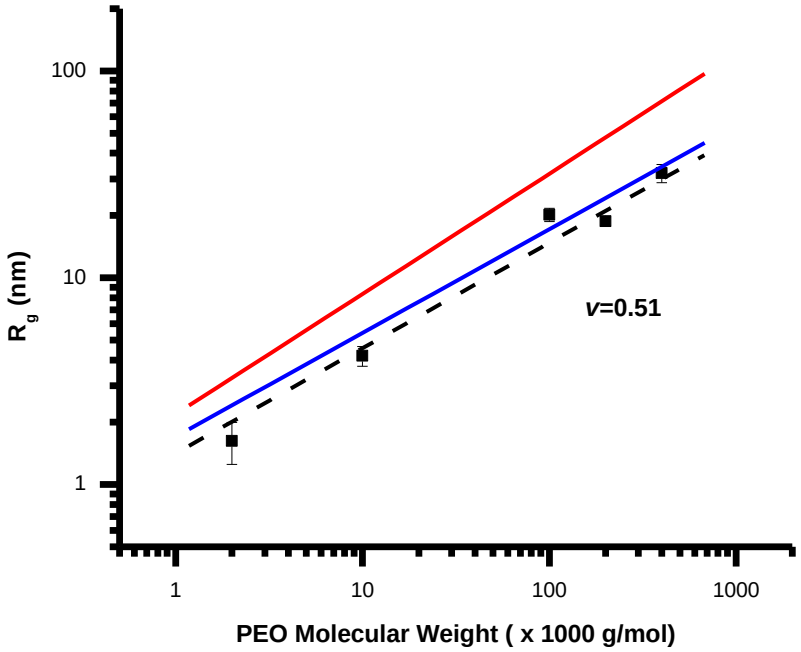


Figure 3.4 The black data points are R_g's of PEO's plotted as a function of molecular weights at T = 60°C. Black dashed line is linear fit to data points. Blue line represents the theoretical good solvent boundary whereas red represents theoretical theta solvent boundary.

The blue line represents the good solvent condition whereas the red line represents theta solvent condition. The dashed line is a linear fit to log R_g versus log M_w and has slope of 0.51. Thus, the exponent *v* is 0.51, which indicates that water is theta solvent for PEO at 60 °C. In the Figure 3.5. the R_g's are plotted as a function of temperature for all M_w's of aqueous PEO 1 mg/ml solutions.

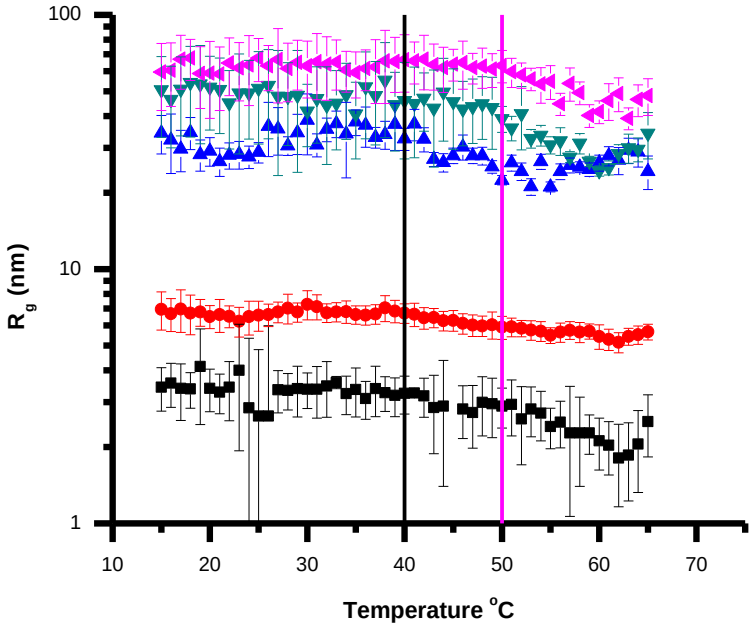


Figure 3.5 Plot of R_g as a function of temperature for different molecular weight PEO's. Black squares are PEO 2k, red circles are PEO 10k, blue triangles are PEO 100k, green triangles PEO 200k and magenta triangles are for PEO 400k.

A decrease in R_g was observed for all measured samples with increasing temperature. In Figure 3.6. R_g values of PEO 2k is plotted as a function of temperature.

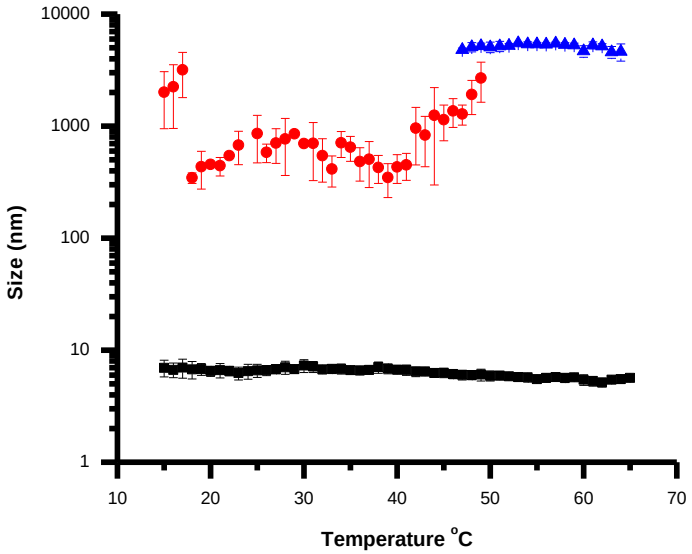


Figure 3.6 Plot of size as a function of temperature for PEO 10k black squares represents single molecule chain, red circles represents bigger particles and blue triangles shows aggregates

R_g measurements of PEO single chains indicate the change of solvent quality with increasing temperature from good solvent at 25 ^oC to theta solvent at 60 ^oC. Though we have not identified the reasons yet, in some DLS measurements we have observed indications of cluster formation exactly at the temperature range (40-50 ^oC) where decrease in R_g was observed. Figure 3.6 shows the analysis of those DLS measurements for PEO-10K. In the temperature range of 15-50 ^oC, R_h of a single PEO chain was constant at ~10 nm. In the same temperature range, there was a second DLS peak at ~500 nm. Between 40-50 ^oC, this second peak increased in size from 500 nm to 3 μm. Above 50 ^oC, only very large aggregates at ~6 μm (the upper limit of size measurements in DLS) were present.

In this study the PEO's having both high and low molecular weights have been investigated in a dilute solution regime. Commercial PEO's chain ends are $-CH_3$. Thus, in this study all of the PEO's are considered to have $-CH_3$ as chain ends. For PEO 2k and 10k the chain ends might affect the hydration[38]. In dilute regime since their chain ends are $-CH_3$ this effect is expected to be observable. This decrease in size might be attributed to the both change in solvent quality and chain end effect.

For PEO water system different researches[37,74,106,107]showed at temperatures lower then LCST, ether-water hydrogen bonds are responsible for the solubility of PEO. This was achieved since formation of ether-water hydrogen bonds results in very favorable ΔG. Increase in temperature leads to break-up of ether-water hydrogen bonding, resulting in reduction of favorable ether-water interaction as relatively persistent water-water hydrogen bonding maintains. These investigations show that there are two driving forces which are hydrogen bonding and hydrophobic interactions. Hydrogen bonding interactions form physical bonds between the oxygen atoms. Hydrophobic interactions tend to favor polymer-polymer attractive interactions[108]. The dimension of PEO in water depends on these interactions. In a good solvent, the solvent-solute interactions work to expand the dimensions of polymer. As the solvent quality decreases the solvent-solute and solute-solute interactions start having competing effects. When they are balanced the chain dimensions corresponds to the dimensions of a volumeless non-interacting polymer chain. In poor solvent regime the polymer chain collapses to have dramatically reduced R_g since the attractive and repulsive forces are no longer balanced[36]. In accordance with the literature it is observed that as the temperature increases water gradually changes from good solvent to theta solvent for PEO regardless of molecular weight. In addition to decreasing size the width of the Gaussian fits deceases. This indicates that as the temperature increases, the sizes are less scattered. In literature it is claimed that PEO coil-coil interactions stronger than

those found for typical polymer coils. That leads efficient packing of water molecules in the interior of the coil and swells the polymer to a size larger than would normally be possible in a solution[51] at low temperature. In the good solvent regime the unimers interior consists of packed water molecules. Since this packing number does not necessarily be the same for each one in a good solvent regime the unimer size is scattered. As the temperature increases and solvent quality decreases the number of the packed water decreases. That result in a less scattered chain sizes. Also the size scattering decreases much more for higher molecular weight PEO's. As the repeating unit increases more water and higher variety of packed water number can be in good solvent condition. As the temperature increases and the solvent quality gets poorer the scattering in size gets smaller. The transition at T~40-45 ^{o}C in Figure. 3.5. is the transition from good solvent to theta solvent. This transition is specially observable in dilute solutions, because the solvent quality is becoming much pronounced with temperature change[56]. In our observations, no formation of multimolecular PEO particles was observed upon temperature increase for most of observations.

PEO clustering was previously explained in terms of many different factors as reviewed in Section 1.2.2. The debate is still on whether the PEO clustering below LCST is an inherent property of the system or not. Many studies[36–56,70,74,106–109] investigated the thermodynamic stability of aqueous PEO solutions. Initially it was suggested that the PEO is not thermodynamically stable in aqueous solutions, so it forms crystals below (LCST)[54]. However, this claim was shown to be valid only at high polymer concentrations (50 % or larger) and at temperatures below 66 ^{o}C[44].No crystallization was reported for dilute aqueous solutions of PEO below LCST. It was later claimed that clusters were actually a concentrated phase of a phase-separated system[52]. Although these studies did not reach to a conclusion, on the clustering of PEO in aqueous solutions below LCST, they gave insight into unique interactions

between PEO and water. It was shown that clustering of PEO in water was heavily influenced by the molecular weight of PEO, concentration of polymer, history of sample, the method used to prepare the solution and temperature.

One of the dominant factors that was claimed to be the driving force for the clustering of PEO in water was the chain end effect. The studies made on chain ends[38,40,43,46] showed that when the end groups of PEO are (hydrophilic) -OH groups they stay dissolved and when the end groups are (hydrophobic) -OCH_3 they form clusters. The hydrophobic end groups tend to orient towards the CH_2-CH_2 parts of the PEO to minimize their interactions with water. The contribution of hydrophilic end groups to overall hydration is especially strong for short polymer chains and decreases with chain length. In dilute concentration regime, the contribution of end group for all kinds of chain ends the hydration increases with temperature and for polymer solutions of higher concentration it decreases with temperature. In general the effect of the end groups on clustering of PEO remain noticeable for dilute aqueous PEO solutions having number of repeat units between 250-500[43,38]. Thus, in this study the chain ends might be the driving force for clustering observations made for PEO 2 000 g/mol and PEO 10 000 g/mol.

If clusters were to form because of a thermodynamic driving force they would depend only on temperature and concentration. However, it is observed that this phenomenon is affected by chain ends, too. One other interpretation of observed PEO clustering phenomenon is the physical cross-links between chains due to the intense hydrogen bonding[42,51]. Long range interactions are not usually observed for linear flexible polymers in good solvents. In case of PEO it is observed that they can maintain long range interactions compared to other linear flexible polymers and this results in larger radius of gyration[51], which are interpreted as clusters. However most recent studies show that the dilute solution of PEO's having low molecular weight (N_{max}=500) are not subjected to

such considerations[41]. As it was stated before, clustering phenomenon is affected from solutions preparation methods and the polymers molecular weight. They depend both on PEO related factors and factors such as impurities[36,37,39,46,49–51] . In some studies the PEO/water solutions are filtrated[46,49] and in these studies no cluster formation is seen so the clustering is attributed to impurities. Additionally the effect of the time is studied, when these samples are tracked for 3 weeks no cluster was seen[46] . However some other studies claim that this filtering breaks down the clusters and they re-form after days to hours[47]. Even though the filtering process is same for all these studies, the method used to prepare solutions differs. This suggests that the ability of PEO to form aggregates depends on history of sample and the method to prepare solutions[45–48,55].

3.2. Critical Micellization of PEO-PPO-PEO triblock copolymer in Aqueous Solutions

3.2.1. Determination of Critical Micellization Temperature of PEO-PPO-PEO triblock copolymers in Aqueous Solution

Figure 3.7 shows the DLS data of 1 mg/ml pluronic F127. There are total of 6100 data points taken in the direction of increasing temperature from 15 ^{o}C to 75 ^{o}C. In the Figure 3.7.a the first 100 data points correspond to 15 ^{o}C, the second 100 to 16 ^{o}C and so. Fig. 3.7.b shows the distribution of the data of Fig. 3.7.a taken at 15 ^{o}C (squares)

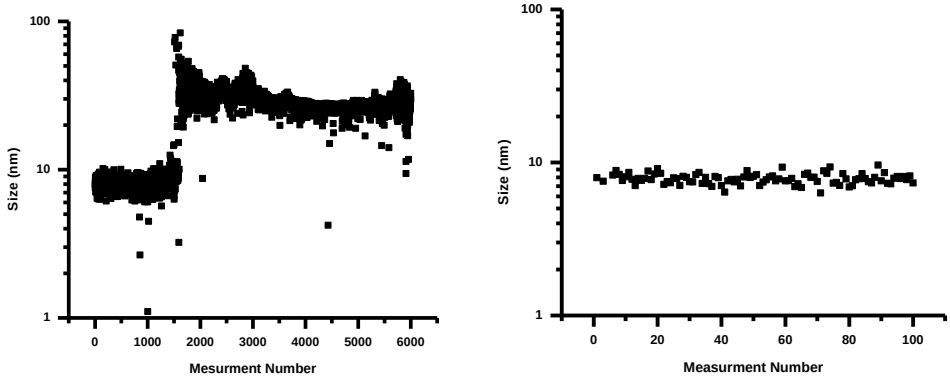


Figure 3.7 Raw DLS data of Aqueous Pluronic F127 solution having 1 mg/ml Concentration (a) Each data point represents the R_h of single F127 chain and micelle sizes in water and each 100 set of measurements corresponds to 1 ^{o}C. First 100 measurements represents data at T= 15^{o}C. Data 100-200 T= 16 ^{o} C and so on. (b) the black squares represents the data taken for T=15 ^{o}C

Unimer size is plotted as a function of measurement number. Size distribution of particles for each temperature was determined and then Gaussian fits were made as shown in Figure 3.8 for data taken at 15 ^{o}C.

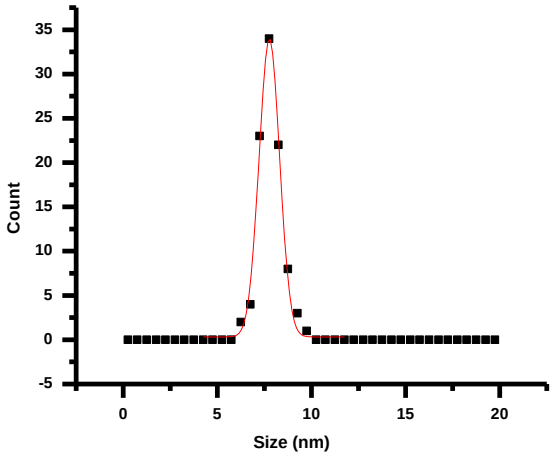


Figure 3.8 Distribution of data taken at 15^{o}C. The solid line is Gaussian fit to the data.

The size corresponding to the peak value of the Gaussian fit, xc, gives the average size of the polymer chains which is 7.76 nm. The width found from fitting Gaussian function to distribution corresponds to 2σ, which is 1.08 nm for this case. The temperature at which particle size increased discontinuously in size vs T graph was assigned as T_{cm} which can be seen in Figure 3.8. The error bars are σ values of each fit.

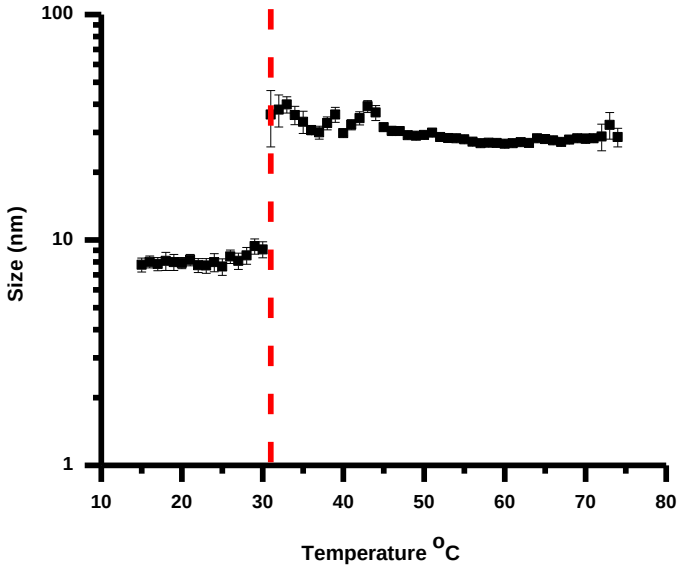


Figure 3.9 Polymer size of F127 1 mg/ml solution as a function of temperature. Red dashed line represents the single polymer chain to micelle transition temperature.

3.2.2. Critical Micellization Temperature of PEO-PPO-PEO Triblock Copolymers in Aqueous Solutions

Figure 3.10 shows the change of critical micellization temperature as a function of polymer concentration for both F127 and F68. As it can be seen from Figure 3.10 as polymer concentration increases T_{cm} decreases for all pluronics.

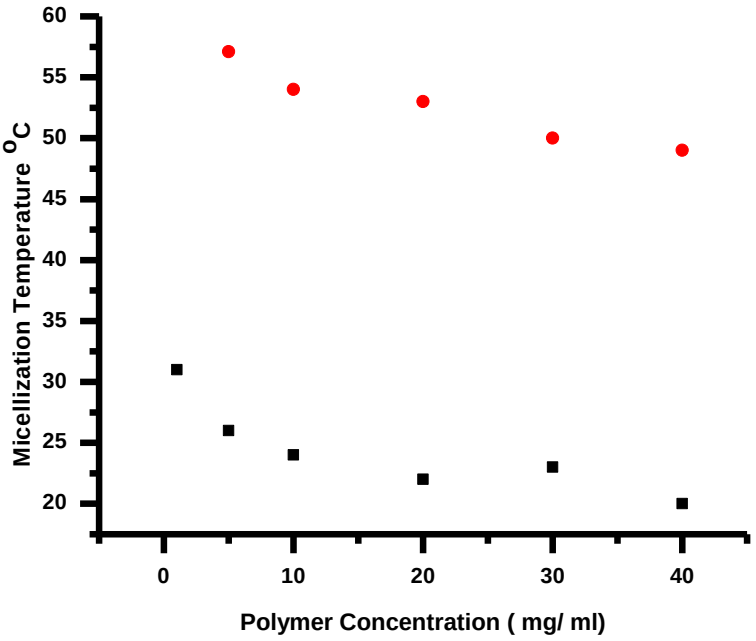


Figure 3.10 T_{cm} of F127 as a function of concentration (black squares), T_{cm} of F68 as a function of concentration (red circles)

Critical micellization temperature of pluronic F68 at 1mg/ml is not observed in this study since it is below CMC[28]. Higher hydrophilic ratio increases the solubility of polymer so the T_{cm} of that polymer is higher .For all other concentrations T_{cm} of F68 are higher than F127. The T_{cm} for both triblock copolymers decreases as the polymer concentration increases. This is due to the solubility. The solubility of these polymers are decreased as the temperature increases. The decrease in the solubility results in much favored micelle formation due to increased hydrophobic interactions. When the polymer concentration is higher there are more hydrophobic units in the environment to form micelles. Thus, higher polymer concentration results in lower T_{cm}.

Below T_{cm} the unimer size of F127 was found 8.5±0.5nm and 5.5±0.1nm for F68. The unimer sizes found to be independent from polymer concentration. The sizes of micelles formed at critical micellization temperature fluctuated for 10 ^{o}C. Then they are stabilized at a constant size. The micelles size decreases down to 30±0.5 nm for F127 and 16±0.6 nm for F68. This is probably due to transition from loose to compact micelles as temperature increases. This is consistent with FTIR and SANS studies made on pluronics micellization in water[13,16,23,25,27,98,110]. It is shown that the temperature driven micellization is due to weakened interactions of methyl groups with water molecules. When heated, especially above T_{cm}, the hydrogen bonding interaction of PPO with water molecules are gradually broken, thus forming denser PPO cores[13,16,18,23,25,26,33,94,98,110,111].

Thermodynamic analysis of micellization

Data analyzed thermodynamically using a model that can apply for both phase separation model and mass action law model[28]. The model was applicable to our data because the polymer concentrations were smaller than 5 weight / volume % (50 mg/mL). The model has the following properties:

i) Equilibrium between molecularly dispersed unimers and micelles.

ii) Second in the absence of electrostatic interactions the standard free energy change of 1 mol of amphiphile from solution to micelle phase, ΔG^{o}, can be calculated using the formula,

$$\Delta G^{\circ} = RT \ln(X_{cmc})$$

Equation 3.3

Where R is the gas law constant, T is the absolute temperature, and X_{cmc} is the critical micellization concentration in mole fraction units.

iii) Thirdly, if the phase separation model is the case, the concentration of free surfactant in the presence of micelles is constant and equal to the CMC value and for mass action model the micelle aggregation number is large.

iv) Aggregation number is independent of temperature in the case of mass-action model.

With these assumptions, the standard enthalpy of micellization ΔH^o can be expressed using Gibbs-Helmholz equation as,

$$\Delta H^o = -RT^2\left[\frac{\partial \ln(X_{cmc})}{\partial T}\right]_P = R\left[\frac{\partial \ln(X_{cmc})}{\partial \frac{1}{T}}\right]_P$$

Equation 3.4

The standard entropy of micellization per mole of surfactant, ΔS^o, can be obtained from

$$\Delta S^o = \frac{\Delta H^o - \Delta G^o}{T}$$

Equation 3.5

It has been shown[28] or block copolymer micellization that, within experimental error,

$$\frac{\partial \ln(X_{cmc})}{\partial \frac{1}{T}} = \frac{\partial \ln(X)}{\partial \frac{1}{T_{cmt}}}$$

Equation 3.6

Where X is the concentration expressed as mole fraction and T_{cm} is the critical micellization temperature thus equation becomes,

$$\Delta H^{o} = R\left[\frac{\partial \ln X}{\partial\left(\frac{1}{T_{cmt}}\right)}\right]_{P}$$

Equation 3.7

Figure 3.18. shows the plot of $1/T_{cmt}$ as a function of the logarithm of copolymer concentration expressed as mole-fraction (ln X) for both F127 and F68. The solid lines are linear fits to the data. The slope of the linear fits was used to calculate the standard enthalpy of micellization ΔH°.

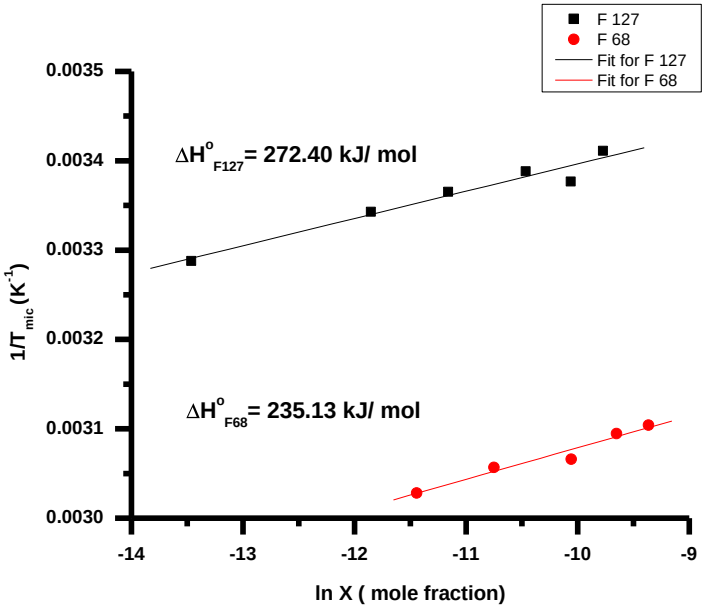


Figure 3.11 Reciprocal Tcm versus ln polymer mole fraction plot for F127 (black squares) and F68 (red circles) . The solid lines are linear fits to data points.

Gibbs free energy of micellization ΔG° and the standard entropy of micellization, ΔS° were calculated at T_{cm} according to Eqn. 3.3 and Eqn. 3.5, respectively. The values were tabulated for all concentrations in Table 3.1.

Table 3.1

Concentration (mg/ml)	$\Delta G°_{F68}$(kJ/mol)	$\Delta S°_{F68}$(kJ/mol)	$\Delta G°_{F127}$(kJ/mol)	$\Delta S°_{F127}$(kJ/mol)
1	-	-	-34.04442	0.88502
5	-31.42172	0.80713	-29.48166	0.88456
10	-29.24138	0.80812	-27.57206	0.88408
20	-27.27241	0.80456	-25.68553	0.88368
30	-25.9322	0.80788	-24.7742	0.87762
40	-25.08145	0.80774	-23.82208	0.88336

The micelle formation in aqueous solutions, as discussed, is due to hydrophobic effect. It was shown that the PEO preserves an open coil structure in water. The increase in temperature results in decreased PEO unimer size since solvent turns into a bad solvent as temperature increases. Being a bad solvent means that the PEO-water interactions are reduced so the hydration of PEO block is reduced[37,42]. The decrease in PEO hydration results decreased screening of PPO blocks from water[24]. Meanwhile the increase in temperature results in progressive dehydration of PPO block[13,16,23,25,110]. This increases the PPO-PPO interactions. The combination of decreased screening due to PEO dehydration and PPO dehydration with temperature results in micellization[13,16,23,25,26,33,94,110,111].

When non-polar molecules introduced into water, water molecules arrange around it in such a way to maximize favorable hydrogen bonding

between them and form cavities. This structuring of the water molecules results in decrease in the water entropy. When hydrocarbon residues aggregate in aqueous solution, the entropy of water increases. The entropy contribution usually dominates the micellization process in aqueous surfactant solutions, with the enthalpy playing a minor role. In the case of pluronics since PPO is the hydrophobic part of the copolymer the Tcm values is related to PPO ratio. The micelles form as the temperature increases in order to minimize water-hydrophobic PPO interaction.

The positive standard enthalpy of micellization, ΔH°, indicates that the transfer of unimers from the solution to the micelle is an enthalpically unfavorable, endothermic process. In the pluronic copolymers, the unfavorable enthalpy component is significant but is overcome by an even stronger entropy effect. The spontaneous formation of thermodynamically stable micelles requires that the free energy, ΔG°, is negative. From these it can be concluded, which is consistent with the literature[13,28], that a positive entropy contribution must be the driving force for micellization of block copolymers.

3.2.3. Change of Critical Micellization Temperature of PEO-PPO-PEO triblock Copolymer in Presence of Series of Sodium Salts

The micellization of pluronic F127 and F68 in presence (chaotropic) of 0.1 M NaSCN and (kosmotropic) Na_2CO_3 is examined. In Figure 3.11, the critical micellization temperatures (T_{cm}) of a) F68 b) F127 are given as function of polymer concentration.

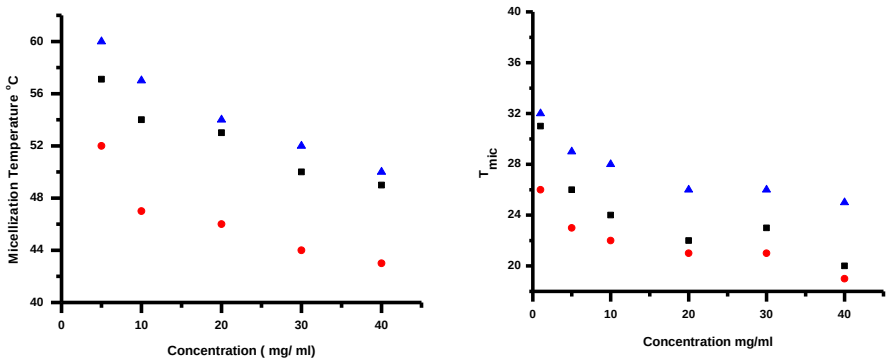


Figure 3.12 Change of T_{cm} with chaotropic and kosmotropic as function of polymer concentration. Black squares represents no salt condition,blue triangles represents the T_{cm} 's in the presence of 0.1 M NaSCN and red circles gives the T_{cm}'s in the presence of 0.1M Na_2CO_3.(a) F127 (b) F68

Blue triangles represent the T_{cm} in the presence of 0.1 M NaSCN and red circles gives the T_{cm}'s in the presence of 0.1M Na_2CO_3. As it can be seen from the figure 3.11 too the T_{cm}'s of copolymers altered significantly in the presence of salts. This data suggests that T_{cm}'s of pluronics behaves differently in the presence of chaotropes and kosmotropes. For both copolymers the Tcm's of pluronics observed to decrease in the presence of kosmotrope salt Na_2CO_3. And T_{cm}'s increased in the presence of chaotrope salt NaSCN.

The kosmotropic anion increases the structuring of water molecules around the anion. Due the increased structuring there is dehydration of both blocks. So with the increase in temperature the salt affects the dehydration more pronounced then no salt condition. Thus a decrease in T_{cm} is observed, $\Delta T_{cm} < 0$. In contrary when a chaotropic anion is induced in the system, the structuring of water is decreased, which results in increase in Tcm, $\Delta T_{cm} > 0$. Even though the temperature driven micellization process is affected by both polymer blocks as it is discussed at section 3.2. 1 the dominant block is PPO.

So the decrease in salt effect in the case of lower PPO ratio is expected which is also consistent with our previous data and literature[14,19,20,22,27,29,35,110,112,113].

In the second part the T_{cm}'s of F127 in presence of 5 sodium salts determined, NaSCN, Na_2CO_3, NaCl, NaI, and $NaCH_3COO$. F 127 concentration is kept constant at 1 mg/ml and the salt concentrations varied between 0.05-0.3M. In the Figure 3. 12 the T_{cm}'s of aqueous pluronic F127 solutions plotted as function of increasing salt concentrations.

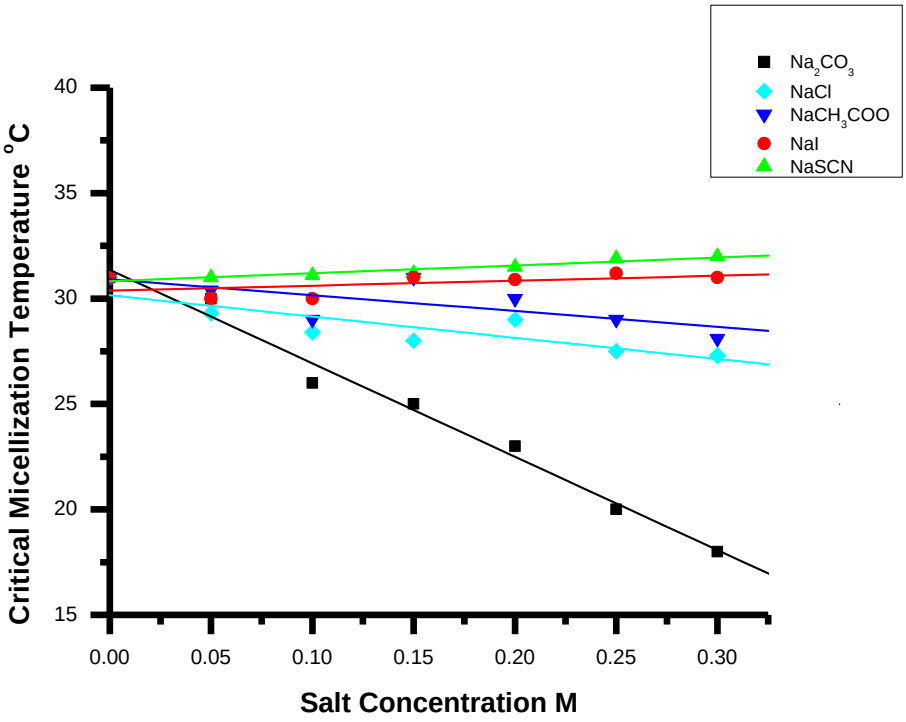


Figure 3.13 The change of T_{cm} of 1 mg/ml aqueous F127 solutions with the concentration of various sodium salts. The solid lines are only for guide to eye.

In this study the change in Tcm's with salts are studied for low concentration regime. As it was stated in introduction the presence of salts

affects the unimer to micellization transition temperatures through three mechanisms, hydration entropy, interfacial tension and direct anion binding. Direct binding of anions does not effect the transitions linearly due to saturation. In this study all the T_{cm} dependences were observed to be linear. So the direct binding of anions to thought to be not so effective. The T_{cm}'s linearly decreased with increasing kosmotropic anion concentration. In the presence of chaotropic anions T_{cm}'s increased slightly. The deviation from no salt T_{cm} values of F127 is more pronounced for kosmotropic anions. The large T_{cm} change in the presence of Na_2CO_3 salt is attributed to the salts effect on the hydration entropy. And the observation of linear dependence of T_{cm} with increase in salt at low polymer and salt concentrations is consistent with the literature[22,27,35].

The results presented above clearly show a transition in aqueous PEO-PPO-PEO triblock copolymer solutions at T = 31 oC for F127 and at T = 57 ^{o}C for F68 (critical micellization temperature) from unimers at low temperatures to spherical micelles at high temperatures. T_{cm} was controlled by addition of various sodium salts at different concentrations. Knowing T_{cm} values under different conditions, the slow self-assembly of this system into fiberlike aggregates below and above T_{cm} will be presented in the next section.

3.3. Self-Assembly of PEO-PPO-PEO Below Critical Micellization Temperature

The 1mg/ml PEO-PPO-PEO triblock copolymer solutions with and without the salts are prepared in water. These solutions are kept below and above critical micellization temperature for several weeks.

The salt concentration is chosento be 0.1 M because all of the salt-polymer solutions Tcm are above the experimental temperature. Table 3.2. shows the self assembled aggregates that are formed in solutions. The aggregates are not observed for aqueous polymer that does not contain series

of sodium salts when kept below critical micellization temperature. The aggregates were investigated by optical microscopy Table 3.2. and in SEM Table 3.3.

Table 3.2 Optical Microscopy Images

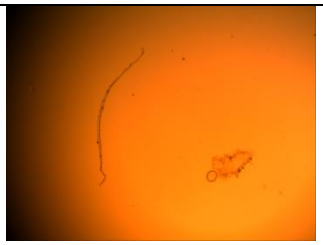
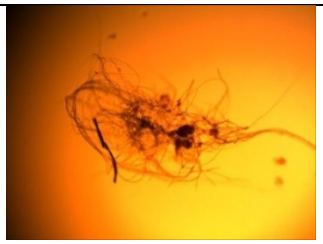
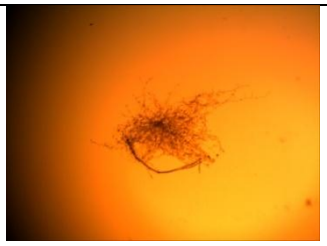
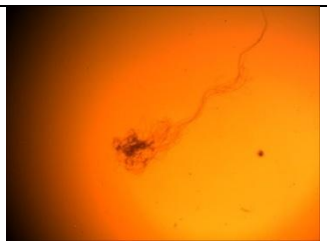
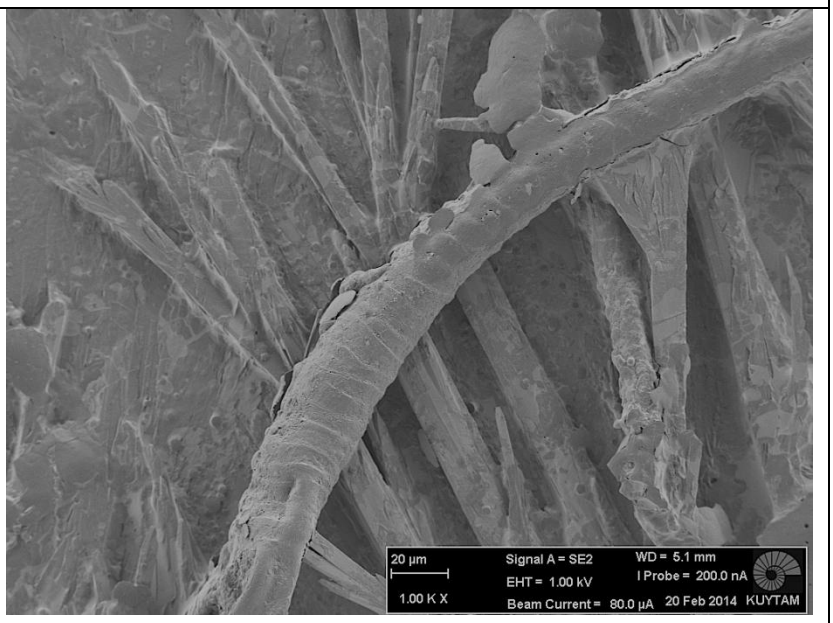
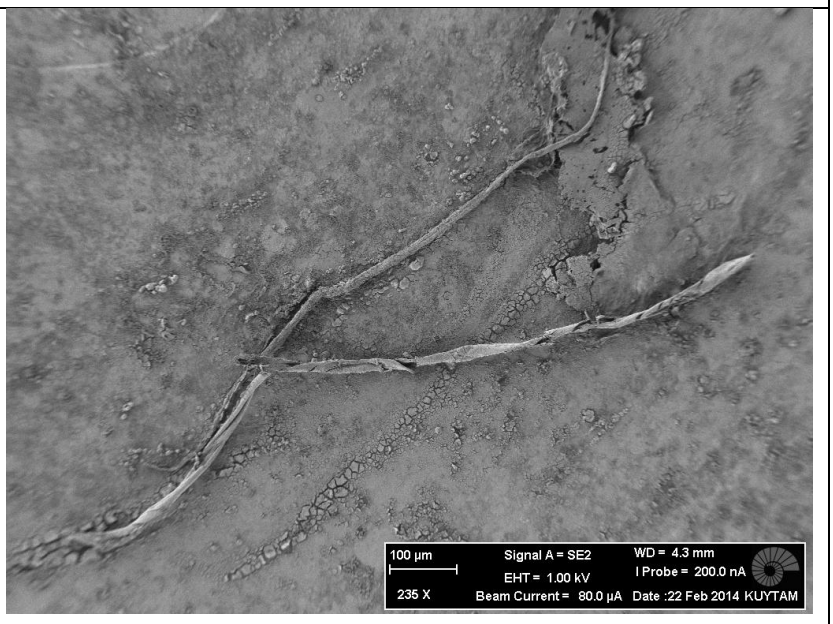
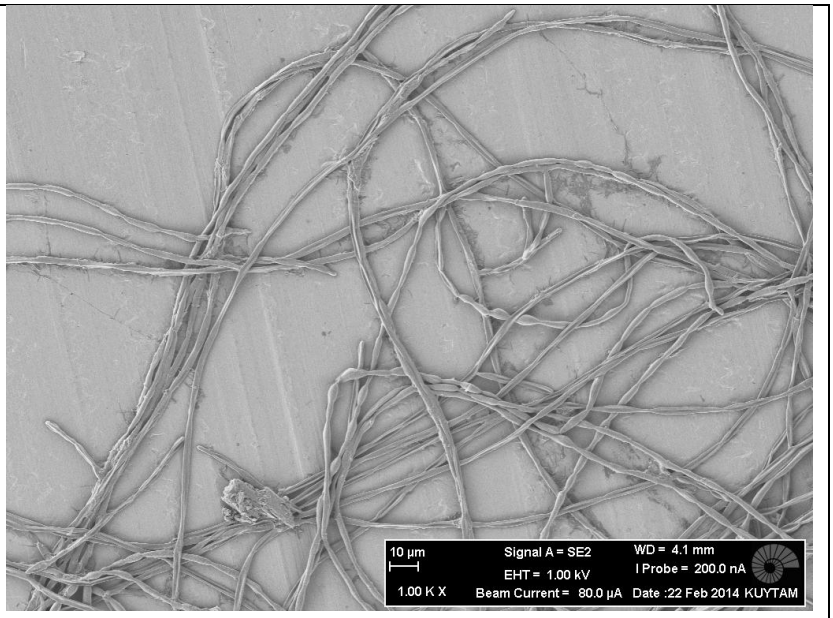
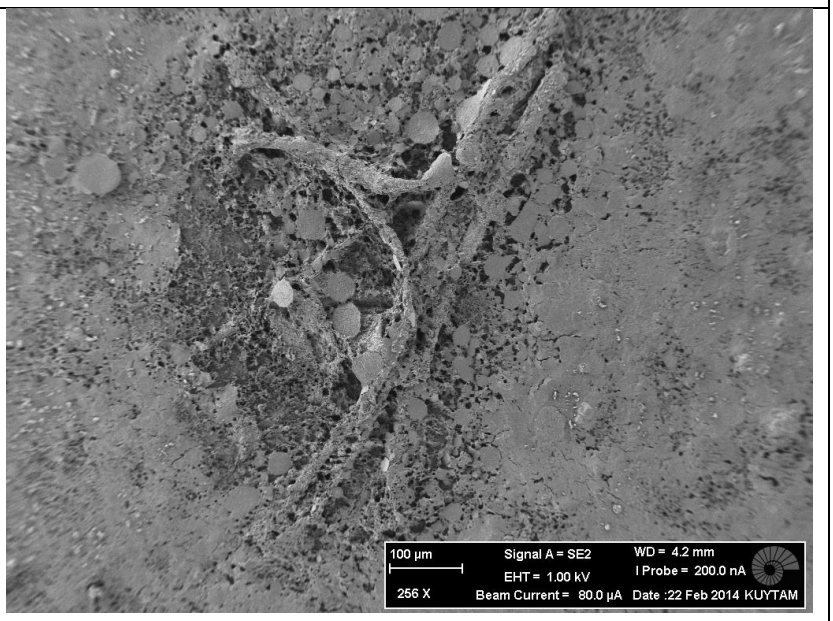
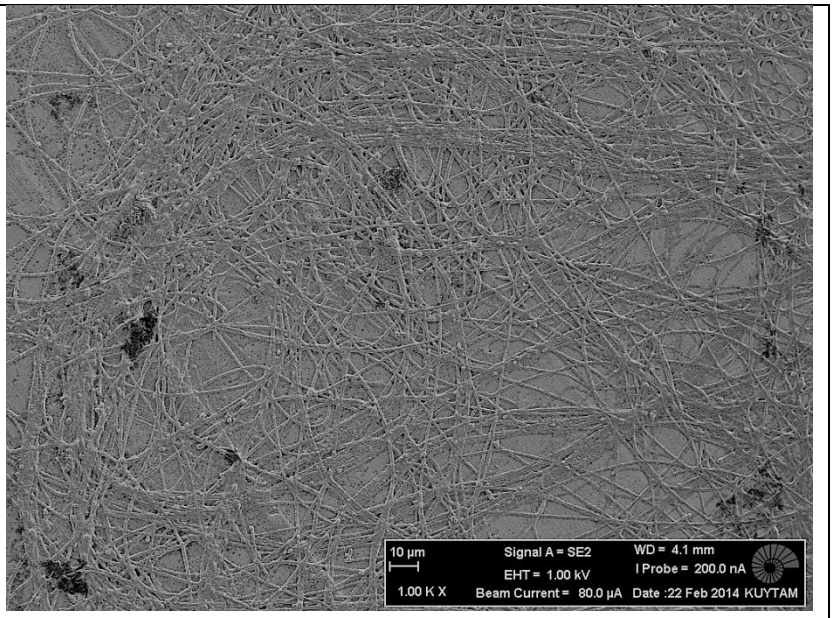
Salt concentration 0.1M	Temperature Kept 25	Critical Micellization Temperature	Temperature Kept 50
CO_3^{2-}		26	No aggregate
Cl^-		28.4	x
CH_3COO^-		29	x
I^-		30	x
SCN^-		31	x

Table 3.3 SEM Images

Salt (0.1M)	SEM Image
Na_2CO_3	
NaCl	

$NaCH_3COO$	
NaI	

NaSCN	

When solutions are kept below T_{cm} for all of salts, micron-sized fiber-like aggregates are observed. As it was mentioned in PEO section, there is possible PEO clustering below LCST. This might result in micelle formation below critical micellization temperature. These micelles may stuck together to form cylindrical rods. These may fuse together to form micron sized fibers. Schematic representation of fiber formation is shown in figure 3.13.

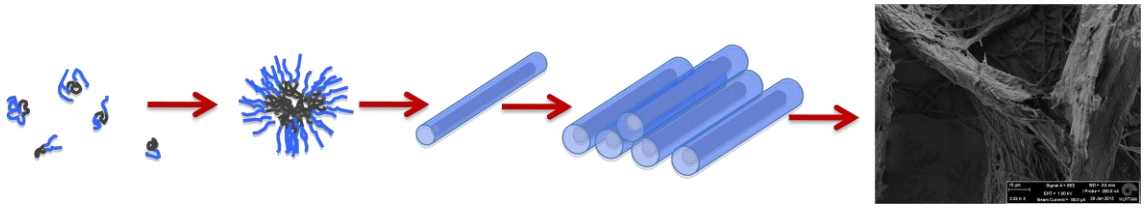


Figure 3.14 Schematic representation of possible fiber formation below T_{cm}

In the figure, grey entangled chains represent PPO blocks whereas blue chains are for PEO blocks. The initial step of micron sized fiber formation is micellization. These single molecules orient themselves to form PPO core and PEO corona structured micelles in water. These micelles fuse to form rods and then micron sized fibers.

4. Conclusion

In this thesis, behavior of PEO homopolymers and PEO containing triblock copolymers in water investigated. In the first part behavior of PEO homopolymer in water studied. Five different molecular weight of PEO were used which are following, 2 000, 10 000, 100 000, 200 000 and 400 000 g/mol The size of single molecule change and possible aggregation upon temperature change was tracked using DLS. The temperature increased from 15 to 65 ^{o}C with 1 ^{o} C increments. Theoretical R_g values were calculated using Flory's theory for monomer sizes. According to this theory the good solvent condition is expressed with the exponent *v*= 0.58 and theta 0.5. The obtained single molecule chain sizes compared with this theoretical exponent *v* values. The *v* is found to be 0.64 for T = 25 ^{o}C and 0.51 for T = 60 ^{o}C. Thus, increase in temperature observed to change the solvent quality from good to theta. Regardless of the molecular weight of the polymer a transition is observed below LCST. For all molecular weights this transition observed to take place between 40-45 ^{o}C. For smaller molecular weights these transitions close to 40 ^{o}C. As molecular weight increases this transition temperature slightly shifts to higher temperatures. In this transition region the sizes of the single molecule chain observed to decrease. This temperature is the inflection point from good to theta solvent. Also in some measurements in this transition region formation of bigger aggregates are observed. This clustering is previously observed in literature. In this thesis the possible reasons for this observation is discussed extensively. However, the origin of this possible clustering below LCST is still uncertain.

In the second part the micellization of triblock copolymers of PEO is studied. The micellization temperatures were determined for two different PEO-PPO-PEO triblock copolymers, which are F127 and F68. The F127 has higher number hydrophobic units whereas F68 has higher number hydrophilic units.

Although they have different hydrophilic to hydrophobic ratios, both pluronics T_{cm} decreased with increasing polymer concentration. Also it was found that pluronic F68 have higher T_{cm}'s compared to F127 T_{cm} 's. Thermodynamical analyses of micellization process were done and hydration enthalpy of the both polymers was calculated. The micellization's hydration enthalpy was found as 272.40 kJ/mol for F127 and 235.13 kJ/mol for F68. The hydration enthalpies were found to be consistent with the previous studies. Thus, according to these findings the formed micelles morphology should have hydrophobic PPO core and hydrophilic PEO corona. Additionally, the effect of the five different sodium salts on T_{cm} was also investigated. The T_{cm}'s was observed to decrease in the presence of kosmotropic salts. For a given polymer concentration the salt concentrations increased. A linear decrease in T_{cm} observed for kosmotropic salts. On the other hand chaotropic salts observed to increase T_{cm}'s. However, in the presence of chaotropic salts no significant change in T_{cm} was observed for increasing salt concentration. The possible interaction mechanism of polymer-salt-water system is discussed.

In the final part, unexpected self-assembled fiberlike aggregates of PEO-PPO-PEO were observed for the first time below the critical micellization. When aqueous PEO-PPO-PEO solutions were kept below T_{cm}'s for extended times self-assembled fiber like aggregates were observed in the presence of salts. By adding various sodium salts, T_{cm} was changed and the observation of self-assembly into fibers below T_{cm} was confirmed. The driving force for this fiber formation thought to be due to the clustering of the PEO below T_{cm}. The possible fiber formation mechanism was discussed.

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Curriculum Vitae

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