Effects of Mixed Stabilizers (Nanoparticles and Surfactant) on Phase Inversion and Stability of Emulsions

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Chemical Engineering

Waterloo, Ontario, Canada, 2009

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Immiscible dispersions of oil and water are encountered in many industries such as food, pharmaceuticals, and petroleum. Phase inversion is a key phenomenon that takes place in such systems whereby the dispersed phase and the continuous phase invert spontaneously. Stabilizers such as surfactants or solid nanoparticles have been used in the past to improve the stability of emulsions. However, the combined effects of surfactants and nanoparticles on phase inversion and stability of oil and water emulsions have not been studied.

This study investigates the synergistic effects of silica nanoparticles (of varying hydrophobicities) and non-ionic surfactant on phase inversion of water-in-oil emulsion to oil-in-water emulsion. The effect of oil viscosity on phase inversion phenomenon is also studied. Stabilizers were initially dispersed in the oil phase with the help of a homogenizer. The water concentration of the system was gradually increased while maintaining the mixing. Online conductivity measurements were carried out to obtain the phase inversion point. Experimental results on the effects of pure stabilizers (either silica nanoparticles or surfactant) and mixed stabilizers (combined silica nanoparticles and surfactant) on phase inversion of emulsions are presented. The stability of these emulsions is also investigated.

From the results obtained in this study it is clear that catastrophic phase inversion phenomenon and stability of water-in-oil emulsions can be controlled with the help of different stabilizers. In order to extend the critical dispersed phase volume fraction at which phase inversion occurs surfactant type stabilizer was found to be more effective than solid nanoparticles. On the other hand, emulsion stability was mainly dominated by solid nanoparticles. The hybrid of the two stabilizers and its effect on phase inversion and stability are discussed in the thesis.

ACKNOWLEDGMENTS

I would like to thank my supervisor Professor Rajinder Pal for giving me the confidence and support to pursue a graduate study in his Rheology and Emulsion Technology group. Professor Pal challenged me to set my benchmark even higher and to focus more on the solution than on the problem. I am deeply grateful for his guidance and valuable advice. His encouragement and suggestions guided me throughout my research and helped me in writing my thesis. I also appreciate his efforts in thoroughly revising the thesis.

Financial support for this research was provided by NSERC in the form of a discovery grant awarded to Professor R. Pal.

Important individuals outside of the University of Waterloo who supported my graduate studies include my family and friends who helped me immensely by encouraging me to grow and expand my ideas. They provided the necessary love and support to continuously encourage me to do my best.

I dedicate this thesis to my mother, father, and sister.

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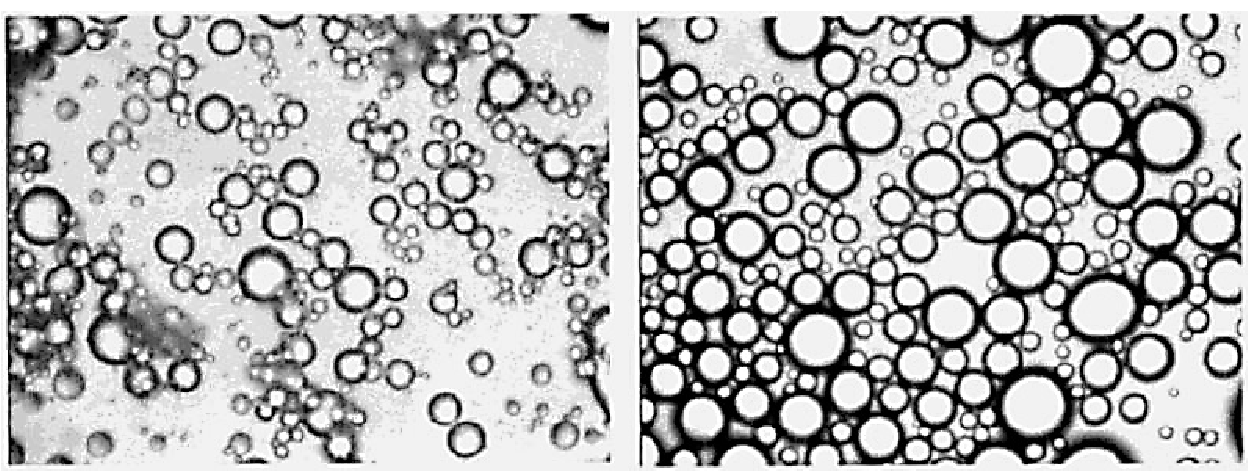
Chapter 1. INTRODUCTION AND OBJECTIVES

1.1. Overview of Emulsions

1.1.1. Definition of an Emulsion

An emulsion is a blend of two immiscible liquids where one liquid (*dispersed or internal phase*) is suspended into another (*continuous or external phase*) in the form of microscopically visible droplets. They are mechanical mixtures of liquids that are immiscible under ordinary conditions, and which may be separated into layers on standing, heating, freezing, by agitation or the addition of other chemicals [1]. Emulsions are generally formed using an organic fluid (mineral oil, silicone oil, kerosene oil, etc.) and a polar liquid (water). Emulsions formed using oil-water systems exist in two morphologies, either water-in-oil (W/O) emulsion or oil-in-water (O/W) emulsion. The microscopic representation of the two types of emulsion formations is shown in Figure 1.1 below:



a) **b)**

Figure 1.1 Optical micrographs of water-oil emulsion systems, a) W/O and b) O/W [2]

1.1.2. Emulsion Stabilizers

The droplets of emulsions can be stabilized against coalescence either by a surfactant or by solid particles. Emulsions stabilized using solid particles are known as Pickering emulsions [1]. In our study, we have utilized a non-ionic surfactant and amorphous silica nanoparticles as the two stabilizers.

1.1.2.1. Surfactants

Surfactants are traditional surface active agents used to lower interfacial tension between two liquids thereby improving the wetting ability as well allowing easier spreading of one liquid on the other. The interfacial tension is lowered due to the adsorption of surfactant molecules at the oil-water interface.

Surfactants are ampiphilic compounds composed of a hydrophobic tail and a hydrophilic head allowing them to be soluble in both the organic and inorganic phases as shown in Figure 1.2. The higher the hydrophobicity (hydrophilicity) of the surfactant molecules, the more soluble it is in the organic (aqueous) phase.

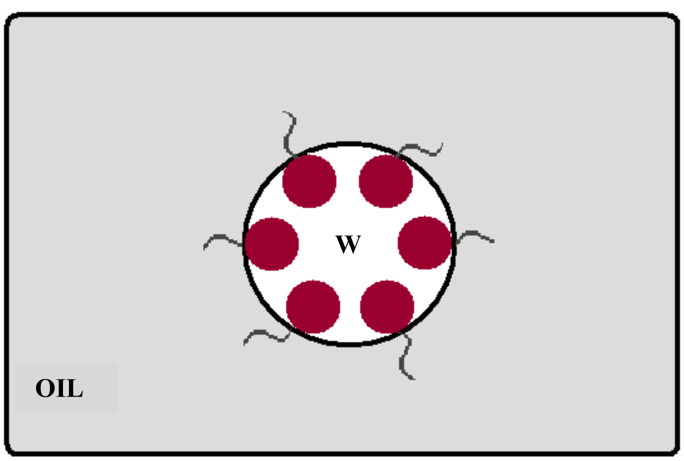


Figure 1.2 Schematic representation of water-in-oil emulsion stabilized using a surfactant

1.1.2.2. Solid Nanoparticles

Solid Nanoparticles are also used as stabilizers to assist in the stabilization of emulsions. Solid nanoparticles rest at the oil-water interface forming a contact angle with the two liquids depending on the hydrophobicity of the particle. A schematic representation of solid particles resting at the oil water interface is shown in Figure 1.3. Lower contact angles favour stable emulsions since they improve the wettability of the dispersed phase on the continuous medium.

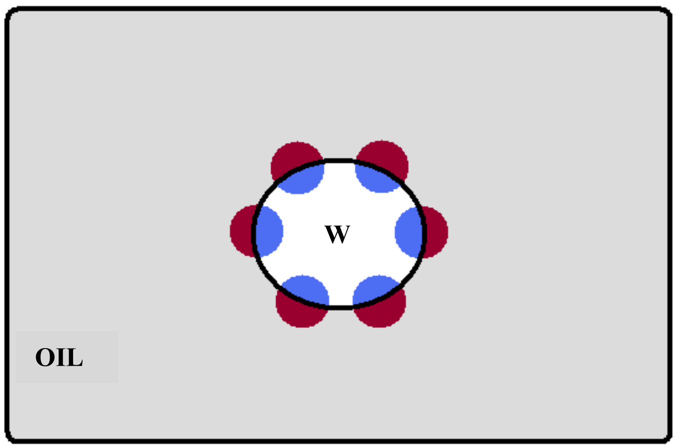


Figure 1.3 Schematic representation of water-in-oil emulsion stabilized using solid particles

Emulsions have numerous applications in several industries. Some emulsion applications are listed in the following section.

1.1.3. Emulsion Applications

The oil and water emulsions are a common occurrence in several industries such as pharmaceuticals, petroleum, food and cosmetics.

a) Pharmaceutical Industry: Since the early days, emulsions have been used as a vehicle for delivery and administration of drugs. Different emulsion systems are also used for drug diagnostic and nutritional purposes. Furthermore, novel emulsion systems have also been developed for improving the availability of drugs in the body (Figure 1.4) and targeting specific sites to ensure more efficient drug targeting [3].

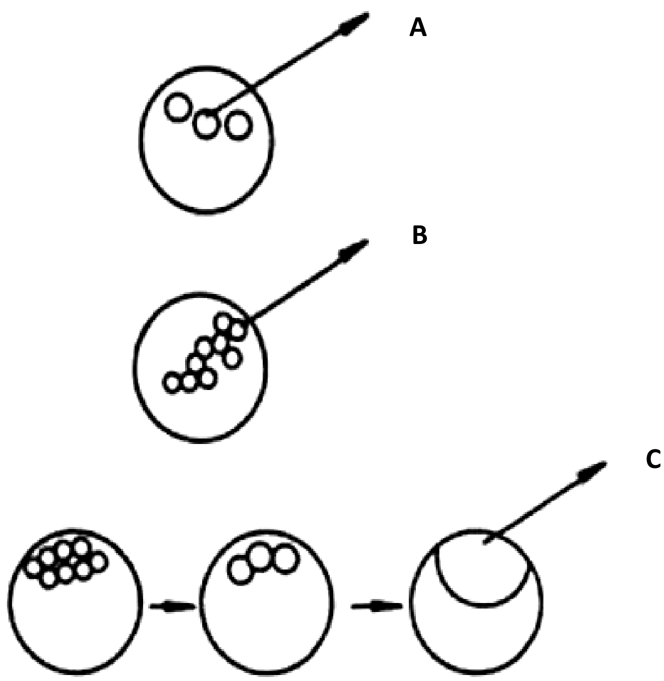


Figure 1.4 Possible mechanisms of release of drug from multiple-emulsion systems. A, diffusion of non-ionized drug through oil; B, diffusion of ionized drug through the oil-water lamellae; C, coalescence of internal aqueous phase and rupture of oil droplet [3]

b) Petroleum Industry: Oil recovery from naturally occurring crude oil produced from onshore and offshore wells often contains large quantities of water in the form of dispersed droplets that need to be accounted for when designing transport pipelines [4]. Approximately 50 percent of the oil present in sedimentary reservoirs remains behind after the use of conventional production methods [4]. Various surfactant containing systems with water as the external phase have been designed and used to enhance oil recovery from reservoirs. Due to the presence of surfactants, oil-aqueous interfacial tension is lowered, which results in enhanced wettability of the oil towards the designed system rather than the rock itself [5]. The designed system must also be able to scrape out rather than bypassing the residual oil. The enhanced recovery methods often produce oil in emulsion form.

c) Food Industry: Processed food items such as butter, milk, mayonnaise are a few examples of food items in emulsion form. For instance, milk or cream is an oil-in-water type emulsion (see Figure 1.5) composed of butterfat triglycerides as the dispersed phase and the aqueous solution of milk proteins, salts and minerals as the continuous phase. Butter is a water-in-oil emulsion with milk proteins, phospholipids and salts as the dispersed phase and the butterfat triglycerides as the external phase [6].

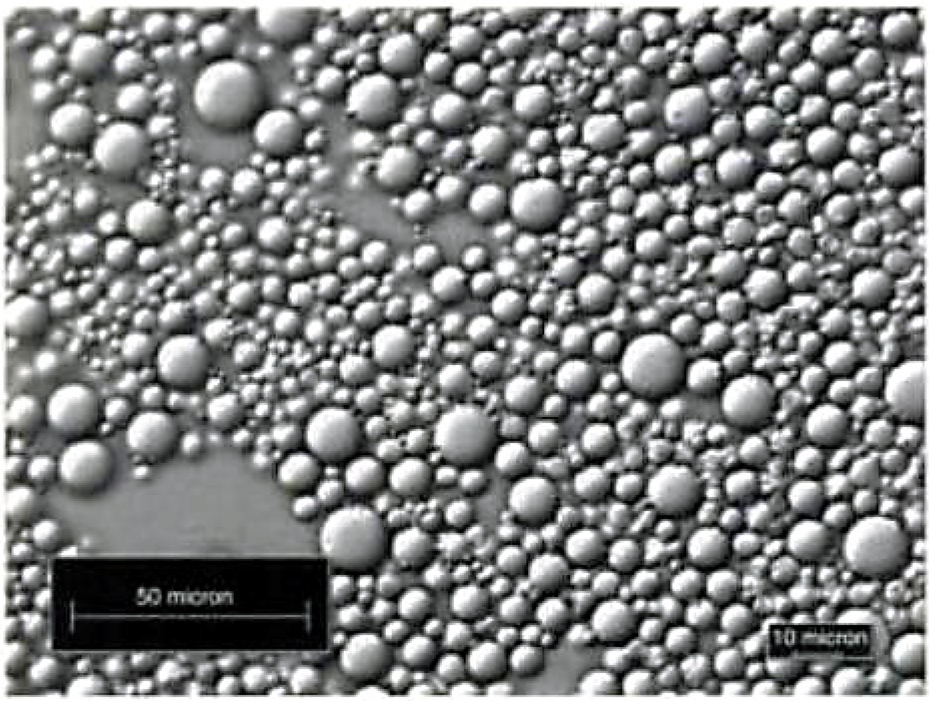


Figure 1.5 An example of a food oil-in-water emulsion (salad dressing) consisting of oil droplets dispersed in aqueous medium [7]

d) Cosmetic Industry: Several cosmetic products are developed using emulsion technology and are known as "cosmetic emulsions". Cosmetic emulsions provide an impenetrable surface layer, which not only prevents penetration of unwanted material but also moderates undue losses of water from skin [8]. Furthermore, they also prove functional in delivering material that filter out UV radiation that could damage the skin. Some of the attributes of cosmetic emulsions include spreadability, smoothness, lustre, and richness of cream.

Emulsion technology is also used in various other industrial fields including [3, 9]:

1. Agriculture
2. Coating and Adhesives
3. Water Treatment
4. Asphalt and explosives
5. Polymerization, and
6. Cleaning and polishing

1.2. Phase Inversion Phenomenon

Phase Inversion is a key phenomenon that takes place in emulsion systems whereby the dispersed phase and the continuous phase invert spontaneously. This phenomenon can occur due to changes in the dispersed phase volume fraction, homogenizing velocity, phase viscosity and stabilizer hydrophobicity etc.

For any emulsion system, there are two ways to attain phase inversion, namely transitional phase inversion and catastrophic phase inversion.

1.2.1. Transitional Phase Inversion

Transitional phase inversion can be achieved by altering the Hydrophile-Lipophile balance (HLB) of any emulsion system at a fixed volume fraction of the dispersed phase. The HLB number is assigned to each surface-active agent. Surface-active compounds with a HLB value that ranges between 3 and 6 are suited to form water-in-oil (W/O) emulsions, while compounds ranging from 8 and 18 are more suitable to form oil-in-water (O/W) emulsions [1].

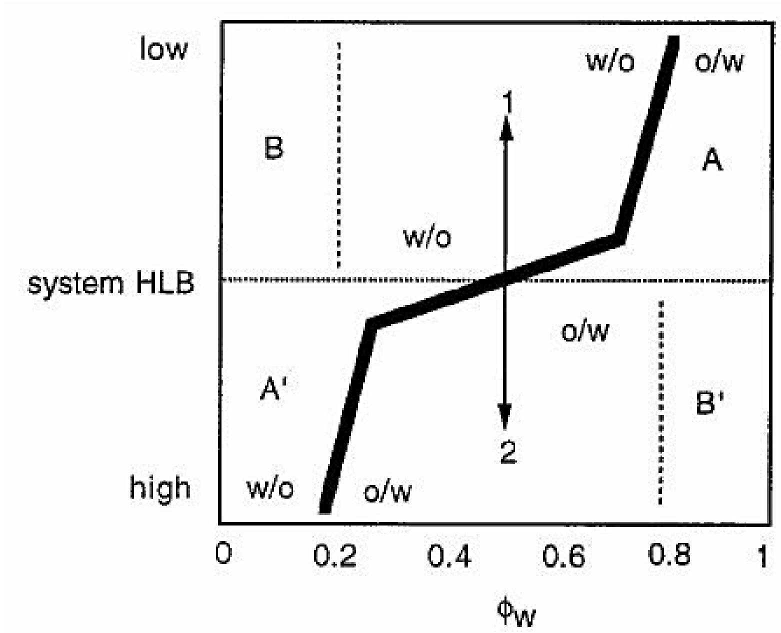


Figure 1.6 Schematic representation of transitional phase inversion phenomenon. Paths 1 to 2 and 2 to 1 depend on the system HLB value [2]

Factors that affect the HLB of any system include properties such as temperature, electrolyte concentration, type of emulsifier etc [10]. As shown in the above figure (Figure 1.6), transitional phase inversion from W/O to O/W emulsion can be achieved by increasing the HLB of the system. In a mixed surfactant system consisting of two surfactants the changes in HLB can be achieved by increasing the ratio of hydrophilic surfactant to hydrophobic surfactant.

1.2.2. Catastrophic Phase Inversion

Catastrophic Phase Inversion is brought about by changing the dispersed phase volume fraction of the system keeping the other parameters constant. The dispersed phase volume fraction at which phase inversion occurs is known as critical dispersed phase volume fraction or the phase inversion point. This system represents a catastrophe showcasing a sudden change in the behaviour of the system due to the gradual change in the system conditions. A diagrammatic representation of catastrophic phase inversion is shown in Figure 1.7:

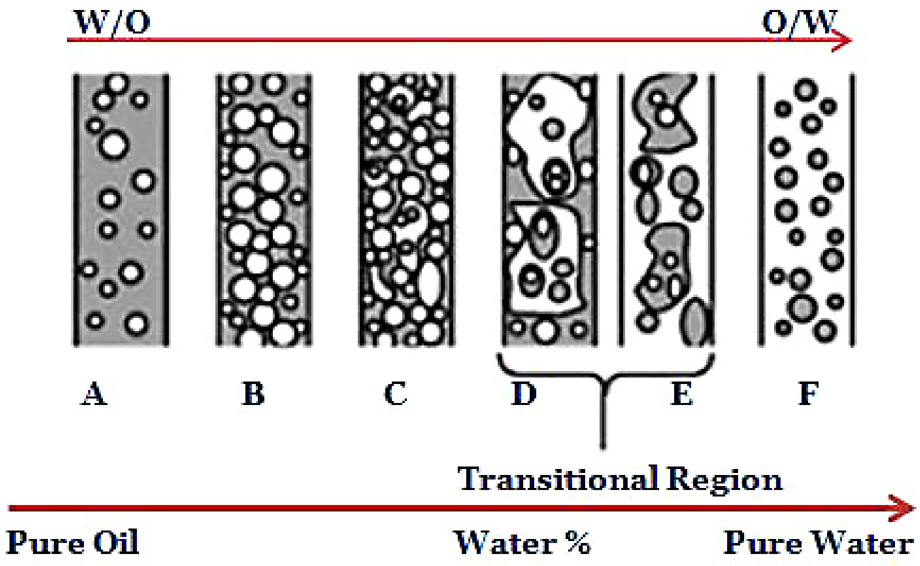


Figure 1.7 Schematic representation of catastrophic phase inversion of a system going from O/W to W/O and vice versa by increasing the dispersed phase fraction of the system [11]

Catastrophic phase inversion also depends on the agitation speed as well as the rate of addition of the dispersed phase. Furthermore, the concentration of dispersed phase (water) at which the system inverts from W/O emulsion to O/W emulsion is not the same as the dispersed phase (oil) concentration at which inversion occurs from O/W emulsion to W/O emulsion morphology.

1.3. Stability of Emulsions

An emulsion is considered to be in a stable state when the dispersed phase droplets are uniformly dispersed in the continuous phase. Emulsion instabilities and breakdown processes that are known to exist include Sedimentation/Creaming, Flocculation, Coalescence, and Ostwald ripening. More details can be found in the following subsections.

1.3.1. Flocculation

Flocculation is a phenomenon whereby the dispersed phase droplets in an emulsion come together to form aggregates (see Figure 1.8). These aggregated droplets are formed due to diffusion or stirring and also due to a weak repulsion potential [10]. Aggregated droplets are separated by a thin layer of film that separates the small droplets and allows them to remain flocculated.

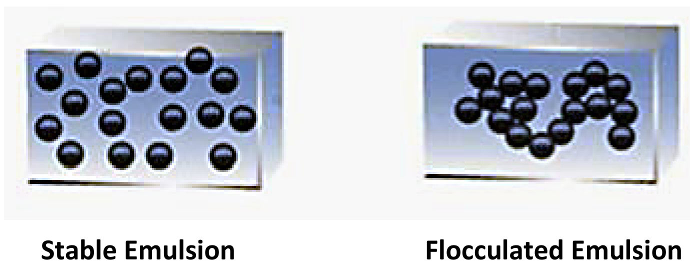


Figure 1.8 Schematic representation of a stable emulsion and a flocculated emulsion. Flocculation occurs as the dispersed phase droplets come together to form flocs [12]

Flocculation usually leads to enhanced creaming since flocs rise faster than individual droplets due to their larger effective radius. Hence, the creamed layer formed due to the creaming process is essentially a large floc. Flocculation eventually leads to another form of instability in emulsions known as coalescence.

1.3.2. Coalescence

After flocculation, coalescence is the next step in the destabilization of emulsions. Once the dispersed phase droplets flocculate, the thickness of the thin layer separating these droplets tends to reduce due to van der Waals attraction [10]. When this thin film ruptures, the flocculated droplets combine to form a larger single droplet. This irreversible phenomenon is known as coalescence (see Figure 1.9).

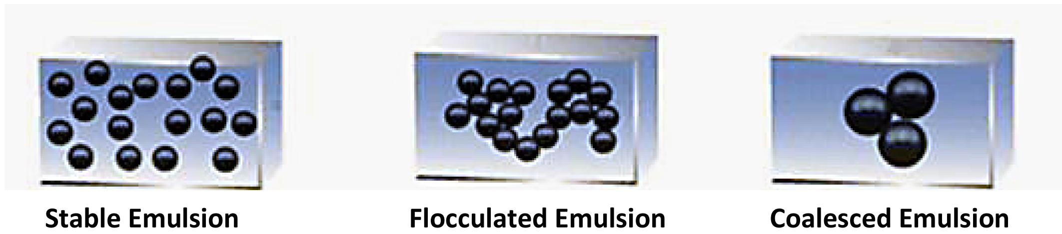


Figure 1.9 Schematic representation of a stable emulsion, flocculated emulsion and a coalesced emulsion. The smaller flocculated droplets fuse together to form larger coalesced droplets [12]

The two deciding factors that lead to coalescence include the rate of film thinning and the eventual rupture of the film. The rate of film thinning depends on the hydrodynamics of film flow and on the forces acting across the film [10]. The film rupture on the other hand depends on the fluctuations in film thickness and on the mechanical properties of the film [10].

1.3.3. Sedimentation and Creaming

For any emulsion system, the dispersed droplets rise through the medium or sink to the bottom of the emulsion based on the difference in the density of the internal and external phases. Depending on the direction of the movement of droplets, the terms sedimentation (*droplets sinking to the bottom*) or creaming (*droplets rising to the top*) are associated with unstable emulsions [10]. The phase separation phenomenon of sedimentation and creaming is enhanced by the dispersed phase droplet size since larger droplets or aggregates move faster through any medium compared to smaller dispersed droplets.

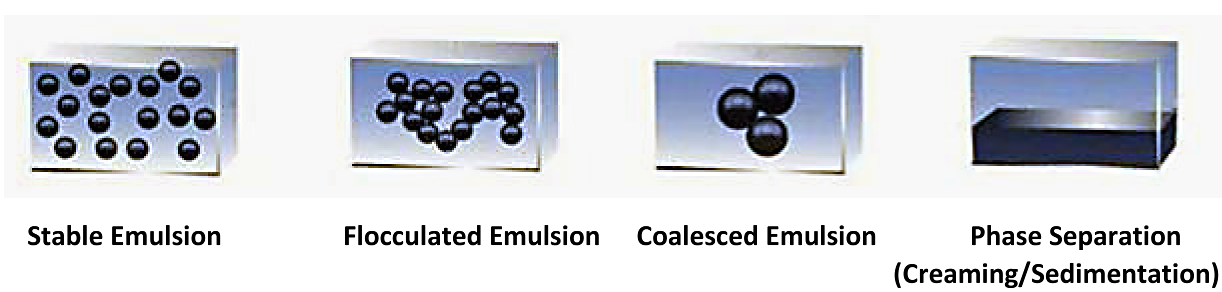


Figure 1.10 Schematic representation of the entire instability process from a stable emulsion to phase separation [12]

Creaming or sedimentation is a result of the action of gravity on droplets. This phenomenon is reversible; with the help of gentle agitation, the droplets can be redistributed uniformly [10]. Emulsion stability is not only dependent on the physical and chemical attributes of the organic and inorganic phases used but also the type of stabilizer used to form the emulsion.

1.4. THESIS OBJECTIVES

In this study, we investigate the synergistic effects of surfactants and silica nanoparticles on catastrophic phase inversion. To our knowledge, no one has studied the effects of mixed stabilizers (nanoparticles and surfactant) on catastrophic phase inversion in emulsions. Specific objectives addressed in the thesis are:

1. to study the effect of individual and mixed stabilizers (surfactant, solid nanoparticles, and mixed surfactant-nanoparticles) on catastrophic phase inversion and stability of emulsions
2. to study the effect of nanoparticle hydrophobicity on the catastrophic phase inversion concentration and stability of emulsion
3. to study the effect of oil viscosity on catastrophic phase inversion using two oils of different viscosities of mineral oil
4. finally, to study the stability of emulsions with respect to coalescence and separation of the dispersed phase in W/O emulsions

Chapter 2. LITERATURE BACKGROUND

There have been numerous studies conducted on emulsion properties in the past. However, extensive technical literature on phase inversion phenomenon is lacking. In recent years, a few research studies have been conducted on phase inversion and stability of emulsions stabilized using different stabilizers [13, 14, 19, and 20].

2.1. Phase Inversion and Emulsion stability using Solid Particles as stabilizers

During the past few years, there has been a growing interest in studying the phase inversion phenomenon in emulsions stabilized with solid particles. Binks and Lumsdon [13] studied phase inversion in pickering emulsions stabilized solely by silica particles. The effects of particle concentration, type of oil, and oil/water ratio on the type and stability of emulsions stabilized by silica particles were determined.

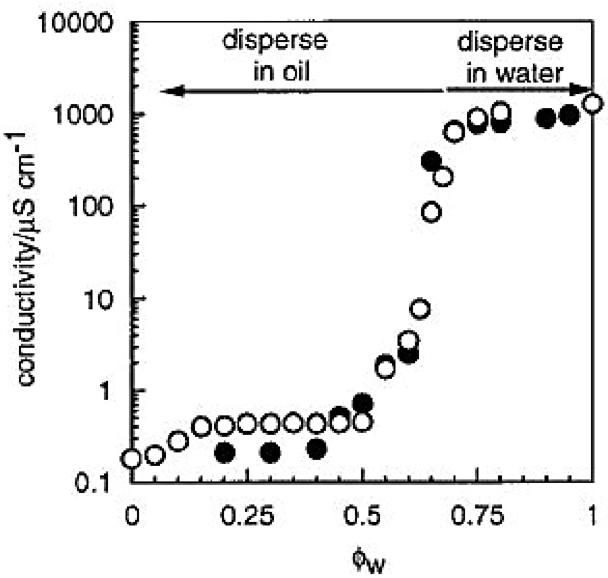


Figure 2.1 Conductivity of toluene-water emulsions stabilized using hydrophobic silica particles. Oil contained 2 wt% particles; water sequentially added to oil (open points) or oil added sequentially to water (closed points) [13]

According to their results (Figure 2.1), the dispersed phase volume fraction where catastrophic phase inversion of emulsion from O/W to W/O morphology and vice versa occurred was around 0.70. They further stated that the preferred emulsion type is W/O irrespective of the type of oil used. They also confirmed that water-in-toluene emulsions stabilized using hydrophobic silica particles can be prepared with a smaller droplet size, which makes the emulsion more stable to coalescence. Furthermore, increasing the particle concentration increased the viscosity of the continuous phase, which improved the stability of emulsions towards sedimentation.

The transitional phase inversion of solid-stabilized emulsions was investigated by Binks and Lumsdon [2] using particle types of different wettability. The oil to water ratio was fixed as 1:1. Using equal volumes of toluene-water emulsion systems, they discovered that inversion from an O/W system to a W/O system occurred on addition of hydrophobic silica to emulsions stabilized by hydrophilic silica particles (see Figure 2.2). Similarly, the inversion of W/O emulsion to O/W emulsion occurred upon the addition of hydrophilic silica particles to a W/O system initially stabilized using hydrophobic silica particles. The emulsions were observed to be very stable towards coalescence before the phase inversion point; however, they showed a significant instability (creaming/sedimentation) around the phase inversion point. Also, the droplet sizes were maximum at the point of inversion, showing greater instability and signs of gravity-induced separation. The authors also reported that an increase in the proportion of hydrophilic silica to hydrophobic silica in a mixed stabilizer system resulted in de-flocculation of water droplets in W/O emulsions.

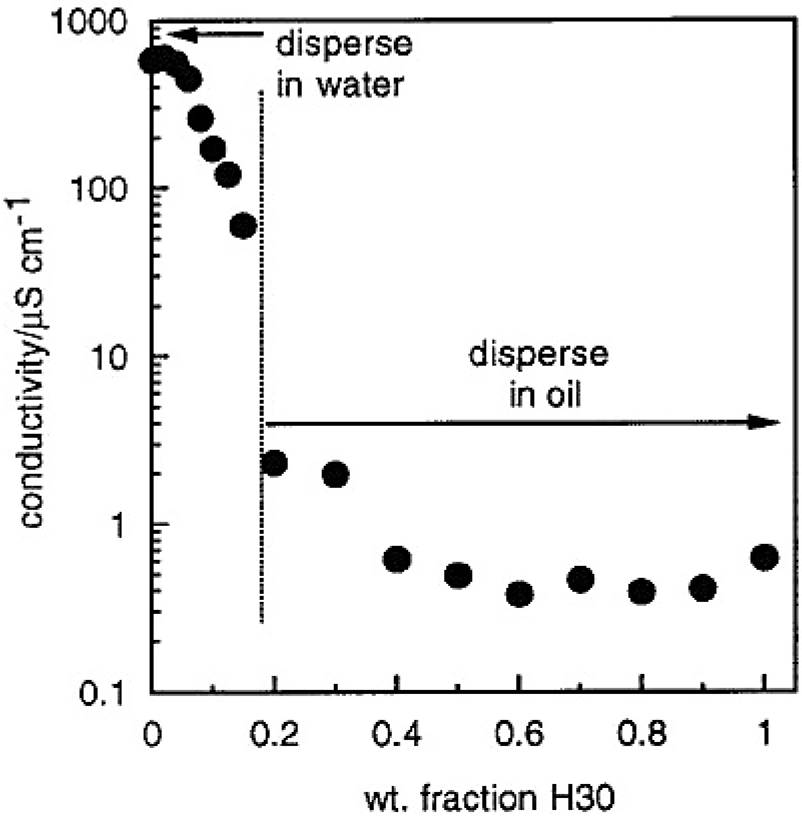


Figure 2.2 Conductivity data for water-toluene emulsion system at ϕ_W = 0.5 containing 2.5 wt% total particles as a function of weight fraction of H30. The hydrophilic particles are initially dispersed in water and hydrophobic particles are initially dispersed in oil [2]

Transitional phase inversion has also been reported by Binks et al. [14]. They showed that emulsions composed of equal volumes of silicone oil and water can be inverted from O/W emulsion to W/O emulsion by increasing the concentration of silica particles (see Figure 2.3). They found that inversion only occurs for systems stabilized with particles of intermediate hydrophobicity. They also confirmed that hydrophobic particles stabilize only W/O emulsions and highly hydrophilic particles stabilize only O/W emulsions. With regards to the stability of emulsions, they also reported that all emulsions produced using different hydrophobic particles were completely stable to coalescence; however, the emulsions did show signs of creaming and sedimentation with time.

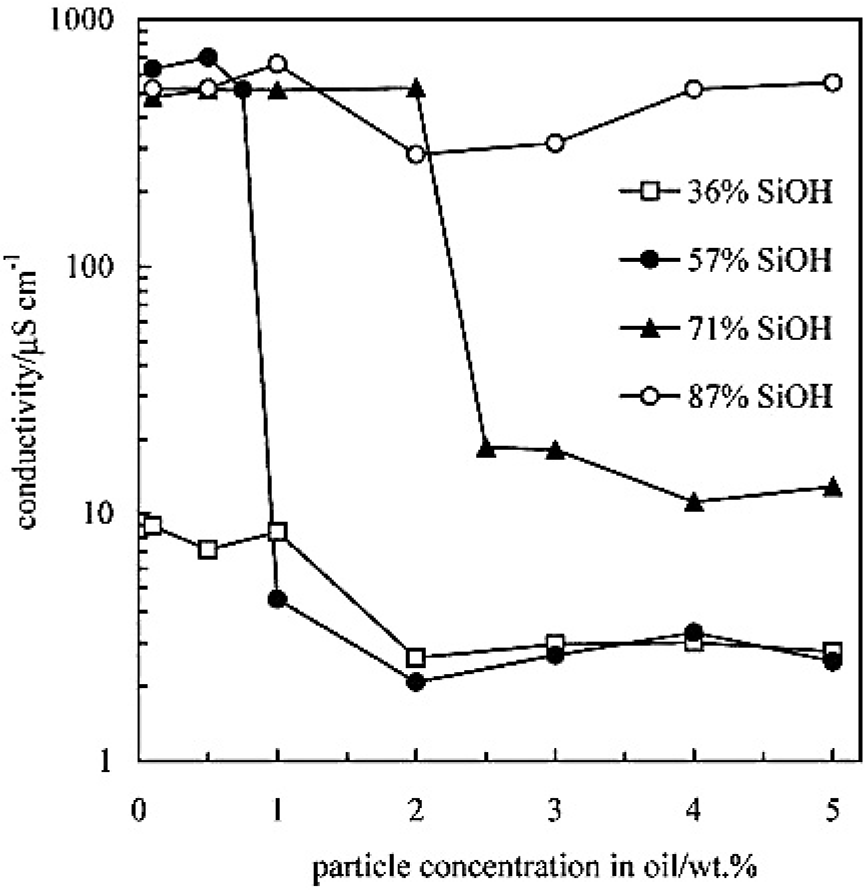
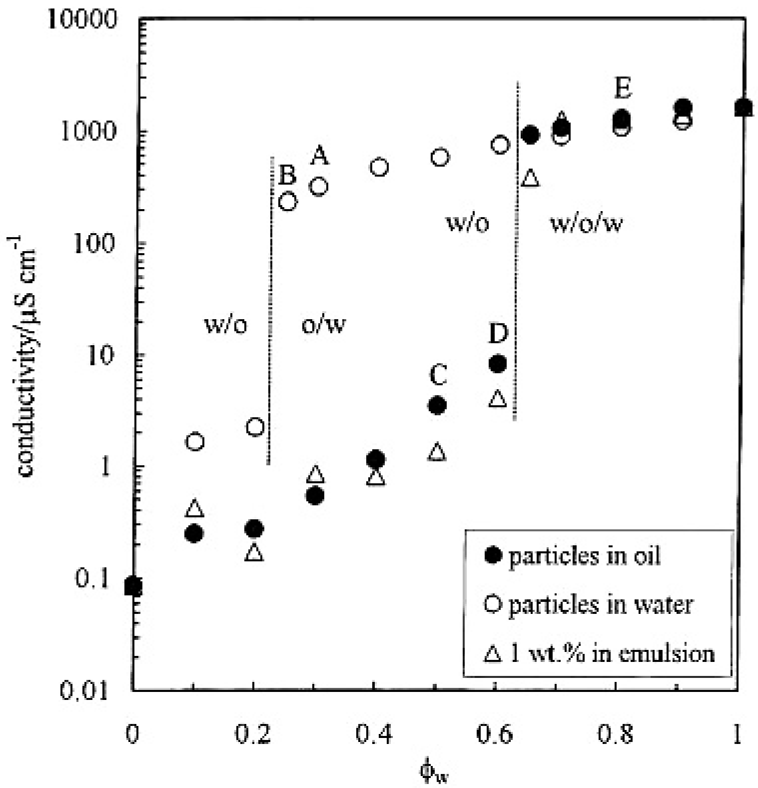


Figure 2.3 Conductivity of silicon oil-water (1:1) emulsions stabilized using silica particles of different hydrophobicities as a function of particle concentration in oil [14]

Binks and Rodriguez [15] studied the effects of initial particle location, oil to water ratio and agitation times on phase inversion in water-triglyceride oil system. They have reported their findings for emulsions prepared in either batch or continuous manner. They found that for the preferred emulsion systems, the preferred continuous phase is the one in which the particles should be dispersed (see Figure 2.4). Thus the inversion of emulsion can be affected by changing the initial particle location, varying the oil:water ratio, and by continued agitation.



<u>Figure 2.4</u> Conductivity and type of water-tricaprylin batch emulsions stabilized by silica particles with 79.9% SiOH as a function of water volume fraction. Open circles, 2wt% particles initially in water; filled circles, 2 wt % particles initially in oil; triangles, 1wt% particles in emulsion originating in oil [15]

Silicone oil and water emulsion systems stabilized solely by silica nanoparticles has been investigated by Binks and Whitby [16]. They studied the influence of particle concentration, oil:water ratio, and emulsification time. They found that as the particle concentration is increased, the coalescence of droplets decreases due to a decrease in the average drop diameter (see Figure 2.5). This in turn lowers the extent of coalescence during drop formation [16]. Also, by increasing the oil volume fraction in emulsions stabilized at fixed particle concentration, the average drop diameter increases until catastrophic phase inversion takes place. For low oil volume fractions, it was observed that the droplet size decreases with increasing emulsification time, thereby limiting coalescence.

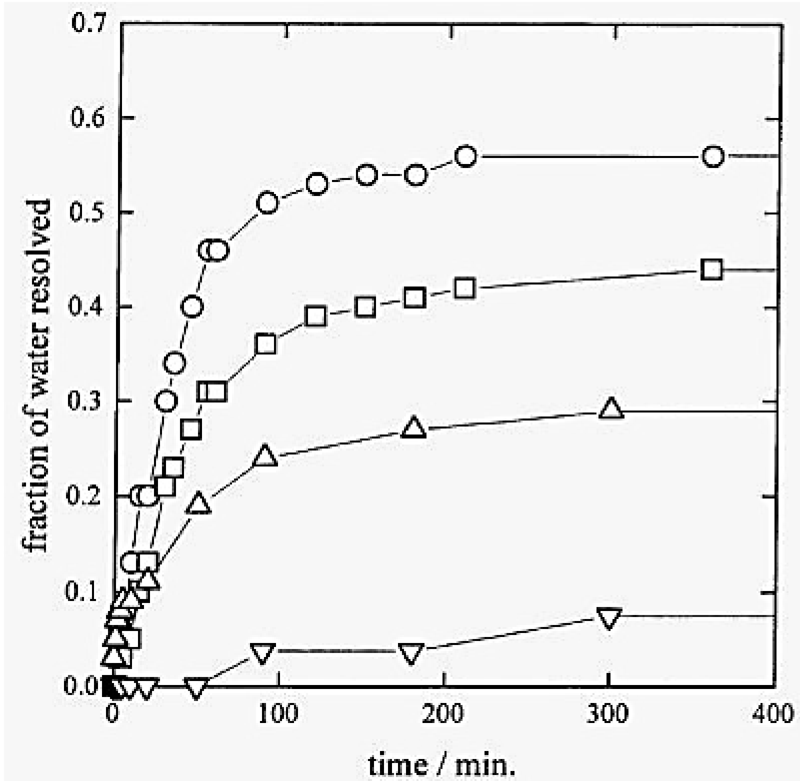


Figure 2.5 Effect of particle concentration on the fraction of water released in emulsions stabilized using hydrophobic silica due to the creaming effect. The concentration of particles in the aqueous phases of the emulsions are (from top to bottom) 0.5, 1, 2, and 5 wt% [16]

The effect of silica particle flocculation on the stability of O/W emulsion systems stabilized by silica particles was studied by Binks and Lumsdon [17]. The addition of different types of electrolytes on emulsion stability was also investigated. They concluded that the stability of emulsion towards creaming and coalescence is low in the absence of an electrolyte. Moreover, the effect of addition of an electrolyte on emulsion and its stability are dependent on the type of salt used. For NaCl, they reported weak emulsion stability when the particles were flocculated. For $LaCl_3$ and tetraethylammonium bromide (TEAB) the emulsion stability increased drastically when silica particles were weakly flocculated. However, extensive flocculation of silica particles led to the destabilization of emulsions.

2.2. Phase Inversion and Emulsion stability using Surfactants

In comparison with pickering (solid-stabilized) emulsions, inversion and stability of emulsions stabilized with surfactants have been studied in greater details. Rondon-Gonzalez et al. [18] discussed the effect of phase viscosity on the inversion point produced by continuous stirring. The trend they observed for any given oil:water ratio; by increasing the viscosity of either of the two phases the inversion point for the system decreases.

They also stated that emulsion inversion produced by continuous stirring is affected by the change in phase viscosity. Different morphologies have been discussed where the change in phase viscosities (oil or water) affect the inversion mechanisms. They have reported that if the viscosities of both mediums are increased at the same time, the inversion occurs through multiple inversion morphology.

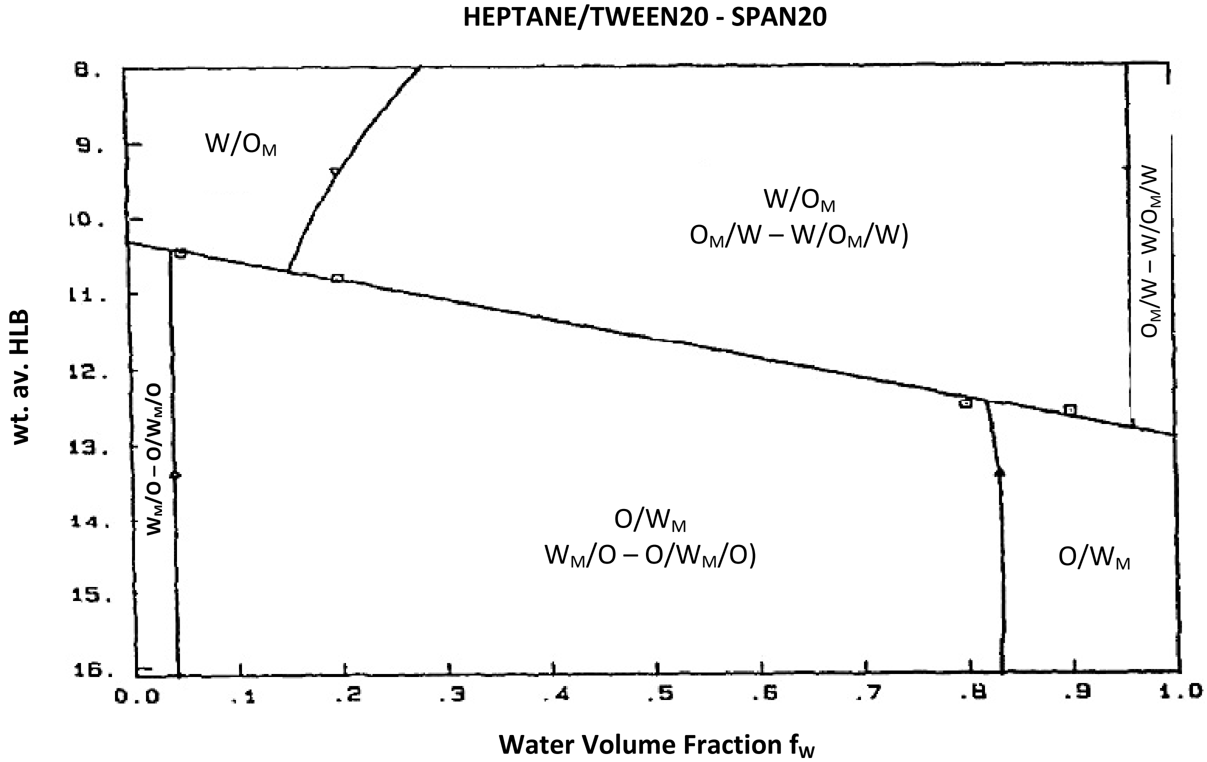
They continued their study on catastrophic phase inversion by studying the effect of water:oil ratio and surfactant concentration on inversion produced by continuous stirring in batch and continuous emulsion systems [19]. They have reported that for inversion occurring from normal to abnormal morphology, the water to oil ratio plays a critical role in determining the stirring required and the kinetics of phase inversion process. The general trend observed from their experiments was that at low dispersed phase volume fraction, it takes longer for the water droplets to incorporate in the oil phase. This slows down the swelling of the oil phase, which increases the critical dispersed phase value that prompts inversion to take place as presented in Table 2.1.

<u>Table 2.1.</u> Inversion time and critical dispersed phase fraction with respect to the concentration of surfactants [19]

total surfactant concn, wt %	dispersed phase fraction (ϕ) at the inversion point			inversion time, s		
	fw 0.6	fw 0.7	fw 0.8	fw 0.6	fw 0.7	fw 0.8
2	0.87	0.86	0.84	6630	8680	15770
4.5	0.83	0.84	0.83	6930	7220	11880
7	0.85	0.85	0.85	7680	11760	19380

Surfactant concentration was also shown to influence the inversion point. At higher water fractions, optimal concentration of surfactants has been shown to achieve shorter inversion times compared to lower water fractions where the time remains the same regardless of the surfactant concentration.

In their preliminary work, Brooks and Richmond [20] studied the phase inversion phenomenon in agitated oil-water systems stabilized with non-ionic surfactants. They established the different types of phase behaviour and clarified the role of surfactant. Their study reports two types of mechanisms: transitional phase inversion which is brought about by changing the HLB of the system and is reversible, and catastrophic inversion caused by changing the water:oil ratio and is irreversible. They also concluded that the inversion behaviour is influenced by the type of surfactant used. Different surfactants have different CMC values and do not provide the same results for different hydrocarbon/water systems. They developed phase diagrams of the type shown in Figure 2.6 for each oil-water-surfactant system.



<u>Figure 2.6</u> Example of phase inversion map for heptanes and SML surfactant at 2 wt% [20]

Brooks and Richmond [21] examined the catastrophic phase inversion of W/O emulsion to O/W system stabilized with non-ionic surfactants. They also studied drop sizes prior to and at the point of catastrophic phase inversion. They concluded that the drop size distribution depends on the stirring speed (see Figure 2.7) and on the rate of addition of the internal phase.

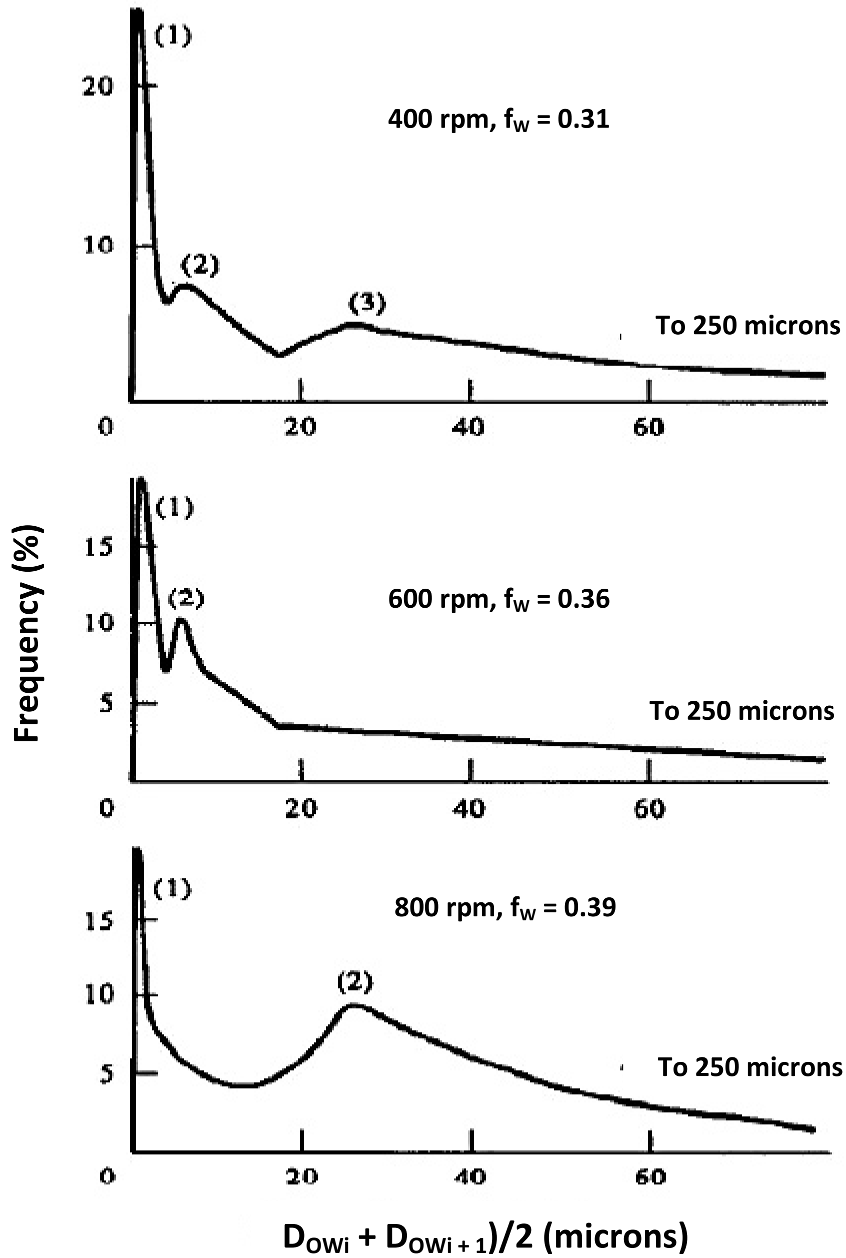


Figure 2.7 Change in drop size distribution with stirrer speed for inverted emulsions. Water addition rate is kept constant at 20dm^3/min [21]

The changes in the drop size distribution during catastrophic phase inversion were shown to be compatible with different mechanisms of drop formation. They also found that direct emulsification produces smaller droplets than those produced through catastrophic phase inversion. This is because droplet coalescence is more efficient than drop breakage.

In a separate article, Brooks and Richmond [22] discussed the effect of oil viscosity on phase inversion. A quantitative analysis of the relationship between drop size of the emulsions prior to inversion and after inversion was also presented. According to their results, an increase in the oil viscosity affects the phase inversion of W/O to O/W morphology. The droplet sizes in any emulsion are controlled by the rate of coalescence whereas the volume fraction of dispersed phase at inversion depends on the oil-phase viscosity as shown in Figure 2.8.

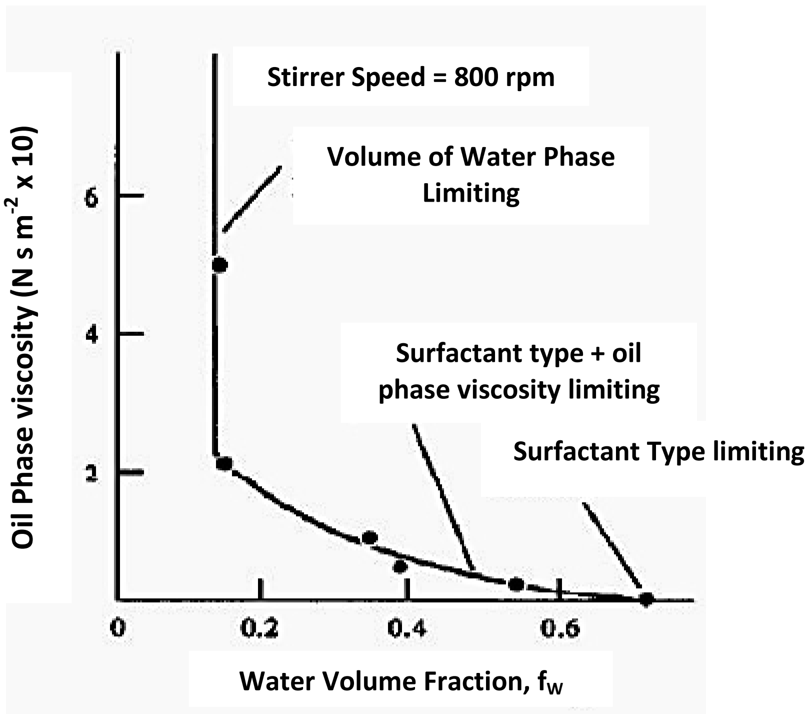


Figure 2.8 Effect of oil viscosity on critical water volume fraction at the point of phase inversion [22]

To supplement their previous work, Brooks and Richmond [23] discussed the phase behaviour of surfactant-oil-water systems. They also discussed the effect of altering the surfactant affinity towards oil or water on transitional phase inversion. Their paper was mainly concerned with the droplet sizes, encountered during transitional phase inversion. They studied the effects of agitation conditions, oil-phase viscosity and surfactant concentration on drop sizes of emulsions produced during transitional phase inversion. They concluded that transitional phase inversion is more efficient than direct emulsification since it produces extremely fine emulsions requiring lower energy input. A comparison between direct emulsification and transitional phase inversion is shown in Figure 2.9.

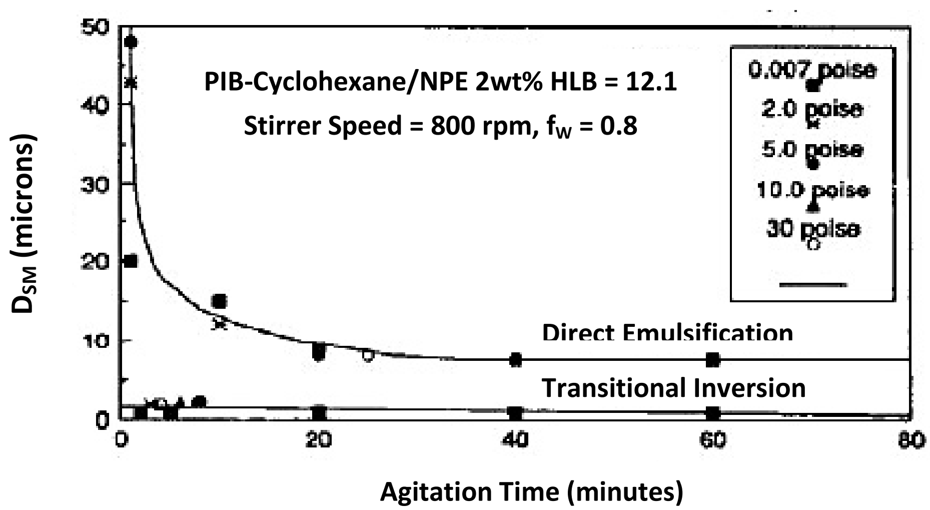


Figure 2.9 Drop size comparisons between Direct and Transitional phase inversion methodology for PIB-cyclohexane-NPE system [23]

Jahanzad et al. [24] recently carried out an investigation where catastrophic phase inversion technique was used to produce finer droplets in comparison with direct emulsification. They utilized cyclohexane/water system with non-ionic surfactants as stabilizers. They concluded that catastrophic phase inversion produces finer emulsions only if multiple droplets are formed at the pre-inversion stage. The phenomenon whereby the droplets of the internal phase are formed in the pre-inversion stage and then released into the region of post-inversion is responsible for the formation for finer droplets. They also found that multiple droplets are formed containing pre-formed fine droplets in their internal structure are formed only at high surfactant concentrations. Figure 2.10 shows some of their results on droplet sizes.

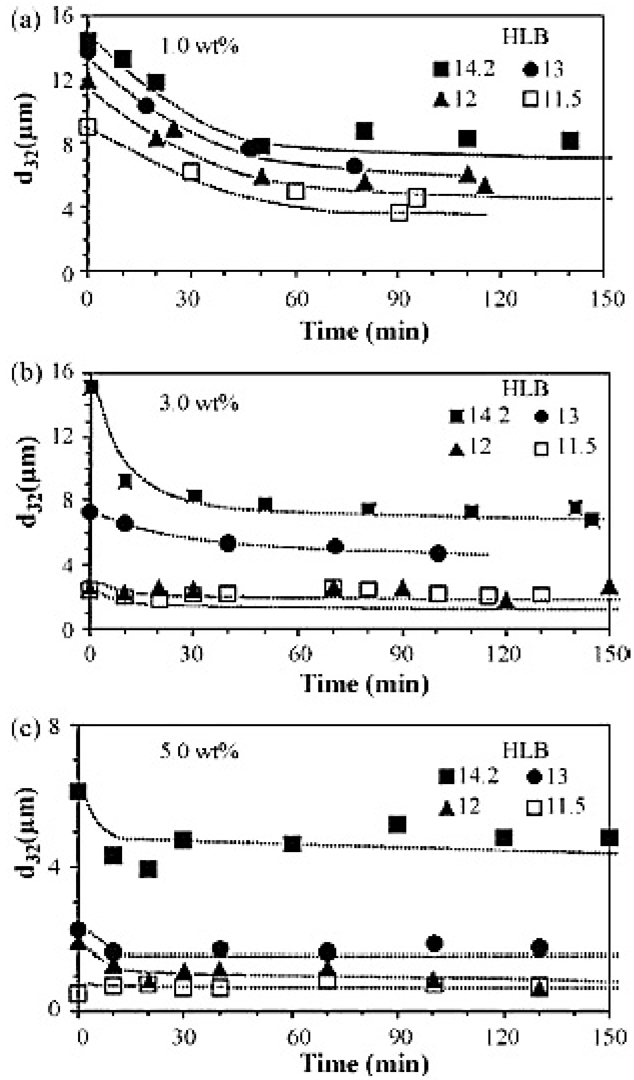


Figure 2.10 Size of oil droplets with respect to time in the post-inversion regime for different surfactant and HLBs [24]

Formation of nano-emulsions by means of emulsion phase inversion was studied in detail by Fernandez et al. [25]. They studied emulsion systems consisting of paraffin oil, water and a mixture of non-ionic surfactants and fatty alcohols. Their work determined the effects of route of preparation of emulsions and surfactant concentration on drop size distribution. They concluded that emulsions prepared through phase inversion have much finer droplets than the ones produced through mechanical shear alone. Also, low interfacial tension facilitates the droplet formation as the resulting droplet size distribution is highly dependent on surfactant to oil ratio.

The mechanism of catastrophic phase inversion has been studied in detail by Bouchama et al. [26]. They studied paraffin oil-water—Triton X-100 systems. The incremental volume of the dispersed phase that is added sequentially to the emulsion before phase inversion plays a vital role in determining the point of phase inversion (see Figure 2.11).

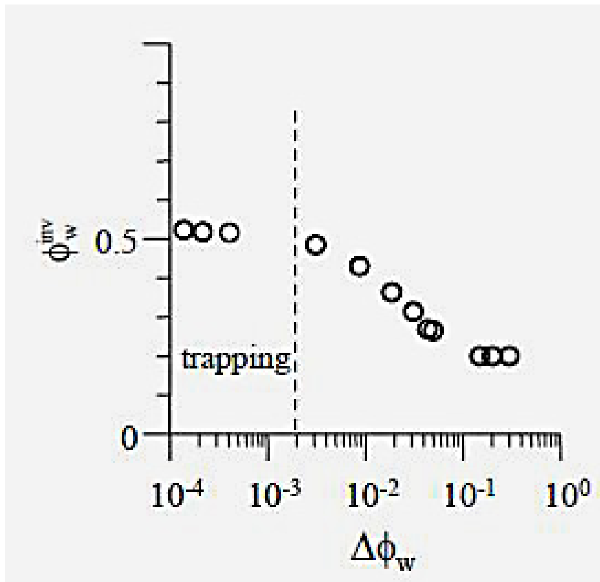


Figure 2.11 Phase inversion points for emulsions going from W/O to O/W morphology as a function of $\Delta\phi_W$ [26]

They found that for smaller aliquots of the dispersed phase addition, the dispersed phase volume fraction at which phase inversion occurs shifts to a much higher value [26]. This behaviour was explained in terms of the formation of multiple emulsions. This concept whereby small amounts of dispersed phase are added sequentially provides a better control over the phase inversion point allowing formation of emulsions with higher dispersed phase volume fractions.

Chapter 3. MATERIALS AND METHODOLOGY

A series of experiments were carried out to study the effects of pure and mixed stabilizers on phase inversion in oil-water emulsion systems. The first three sets of experiments were conducted with three pure stabilizers (non-ionic surfactant, 50% hydrophobic nanoparticles, and 30% hydrophobic nanoparticles) with varying concentrations. The other two sets of experiments dealt with the effects of mixed nanoparticle/surfactant stabilizers on phase inversion in emulsions. Similar experiments were repeated for a higher viscosity oil to comprehend the effect of oil viscosity.

3.1. Materials

Specifications for all materials used in the experimental work are outlined in this section.

3.1.1. Types of Oils

The two oils used in this work were white mineral oils obtained from Petro-Canada. The oils were 99% pure and crystal clear with excellent low pour characteristics. They were low in volatility, odourless and colourless [Appendix B]. The specifications are provided in table 3.1:

Table 3.1 Physical properties for the two viscous oils, Purity FG WO 15, WO 35 (Reference: Petro-Canada Tech Data Specification Sheet, Appendix B)

PROPERTY	TEST METHOD	PURITY FG WO	
		WO 15	WO 35
Density, kg/L @ 15°C	D1298	0.847	0.855
Viscosity cSt @ 25°C mPa.s @ 25°C	D445	27 22.9	75.4 64.5
Flash Point, °C	D92	180	220
Pour Point, °C	D97	-18	-18

3.1.2. Type of Surfactant

In our experiments, we used a highly hydrophobic surfactant. The surfactant used was EMSORB 2503, which is a non-ionic surfactant. The chemical name of EMSORB 2503 is sorbitan trioleate, which is a form of ester. Being a sorbitan ester, EMSORB 2503 tends to be more lipophilic or hydrophobic in nature. Exhibiting a low HLB (Hydrophile-Lipophile Balance) value of 1.8 [1] allows EMSORB 2503 to have greater affinity for lipids or water-insoluble compounds. Due to the highly hydrophobic nature of the surfactant, it is widely used to stabilize W/O emulsions.

The chemical structure of the surfactant is shown in Figure 3.1. The physical properties of the surfactant are given in table 3.2.

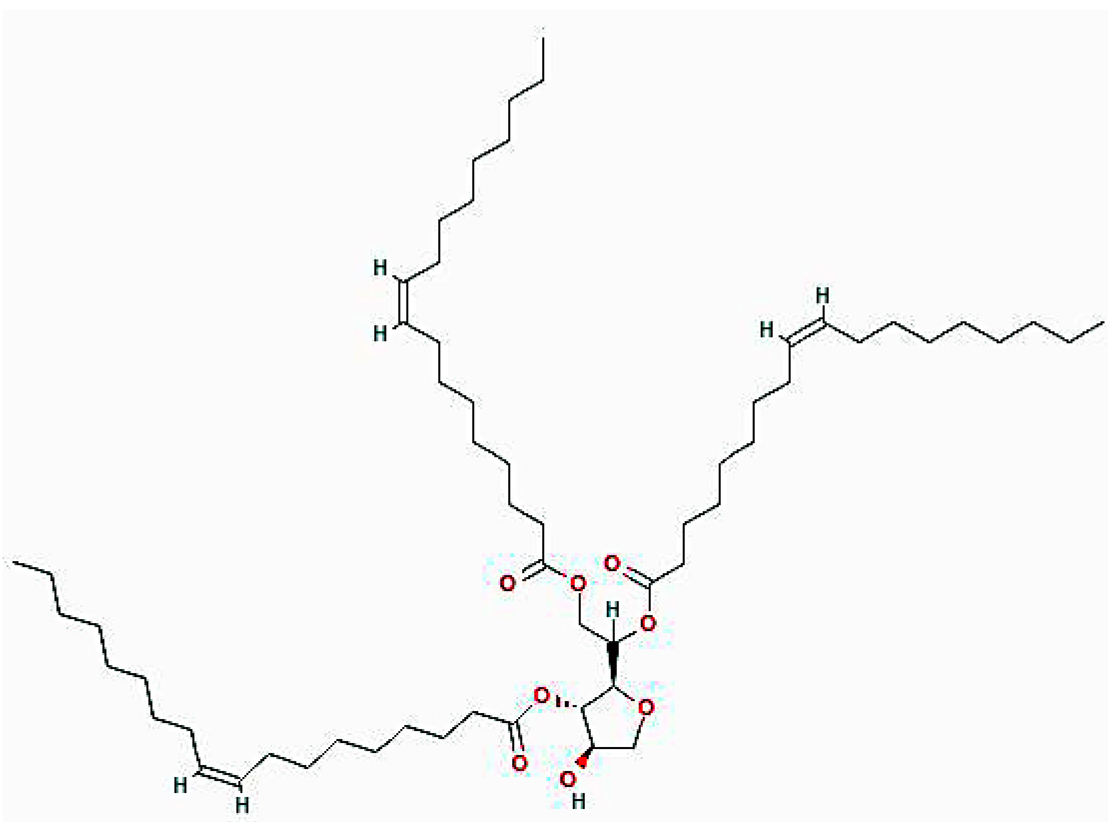


Figure 3.1 Chemical Structure of EMSORB 2503, Sorbitan trioleate [27]

Table 3.2 Physical Properties of EMSORB 2503, Sorbitan trioleate [26]

PROPERTIES	VALUE
Chemical Formula	$C_{60}H_{108}O_8$
Molecular Weight, g/mol	957.51
Derivation	Sorbitol, Fatty Acid
Boiling Point, °C	> 100
Specific Gravity	0.95
Flash Point, °C	> 140
HLB Value	1.8

3.1.3. Types of Silica Nanoparticles

Silica nanoparticles were used as alternative stabilizers. The two grades of silica nanoparticles used were hydrophobic in nature. Pure amorphous silicon dioxide (hydrophilic silica nanoparticle) is reacted with reactive silanes, such as methyl chlorosilanes and hexamethyldisilazane to produce the hydrophobic grade silica. The extent of coating on the hydrophilic silica determines the grade of the hydrophobic silica. They were produced using hydrophilic silica nanoparticles.

In our experiments, we used 30% hydrophobic grade (HDK HKS D) and 50% hydrophobic (HDK H20) grade silica nanoparticles. Some common properties for both grades are given in table 3.3. The physical-chemical properties of the individual silica grades are given in Table 3.4.

Table 3.3 General properties of both hydrophilic and hydrophobic silica nanoparticles, HDK HKS D and HDK H20

TYPICAL GENERAL PROPERTIES	TEST PROCEDURE	VALUE
Si-O_2 Content, %	DIN EN ISO 3262-19	> 99.8
Density of SiO_2, g/l		2200
Silanol group density, SiOH/nm^2		1
Electric resistivity (density 40 g/l), [Ω cm]		> 10^{13}
BET-Surface Area, m^2/g	DIN ISO 9277/DIN 66132	ca. 170

Table 3.4 Physical-Chemical Properties for the two individual silica nanoparticles, HDK HKS D and HDK H20

PHYSICAL-CHEMICAL PROPERTIES	HDK H20	HDK HKS D
BET, Specific Surface Area, m^2/g	200	200
Hydrophobicity, SiOH content	50%	30%
Hydrodynamic Diameter, nm	100	100

3.1.4. Aqueous Phase

The aqueous phase used throughout the experiments was 0.01M NaCl solution. The solution was prepared using deionized water and 99% pure sodium chloride purchased from Sigma-Aldrich. The conductivity of the aqueous phase was 1100 µS/cm.

3.2. Equipment

The equipment used to conduct the experiments are listed with general specifications in table 3.5.

Table 3.5 Specifications of equipment used in the experiments

Equipment	Make	Specification
Homogenizer	Greerco Corporation	Gifford Wood, 1-L, 0-140V
5200 Digital Camera	Nikon	5 MP
Conductivity Meter	Thermo Orion	3-Star Meter
Dual Channel Conductivity Probe	Thermo Orion	013005 MD, 0-200 mS/cm

3.3. Experimental Procedures

3.3.1. Calibration of Conductivity Meter

In order to calibrate the conductivity meter, the nominal cell-constant selection method with a single calibration standard was used [28]. The details of the calibration procedure are described below:

1. Turn on the Thermo Orion 3-star conductivity meter and press the setup key. Select Thermo Orion conductivity standard with a conductivity value of 1413 μS/cm.
2. Using the "up" arrow key, select "COnd" calibration setup. Press the line key to move the icon and the "up" arrow key until CELL is displayed on the screen.
3. Rinse the conductivity probe with deionized water and blot dry with lint free tissue. Insert the conductivity probe into the conductivity standard and stir gently.
4. Press the line select key to move the icon to the bottom line. Manually enter the cell constant value by using the up/down arrows to adjust each digit.
5. Press the line select key to move the icon to the top line and press the measure key to return to the measurement mode.

3.3.2. Study of Phase Inversion

In order to achieve catastrophic phase inversion in different emulsion systems, the following procedure was followed.

1. A known amount of stabilizer (surfactant, silica nanoparticles, or mixed surfactant-nanoparticles) was initially dispersed in the oil phase using a Gifford-Wood homogenizer. In order to allow complete dispersion, the solution was continuously homogenized for 30 minutes.

2. The dispersed phase (0.01M NaCl aqueous solution) was then sequentially added to the oil phase while maintaining the mixing. After each addition of the dispersed phase, the emulsion was homogenized for about 5 minutes before the measurement of the electrical conductivity.
3. The conductivity was measured using Thermo Orion 3-star conductivity meter with a dual channel probe. The conductivity of water-in-oil (W/O) emulsion was very low.
4. Upon inversion of water-in-oil (W/O) emulsion to oil-in-water (O/W) emulsion, a sudden jump in the conductivity was observed. This was due to the presence of electrolytes in the aqueous phase, which allowed the emulsion to conduct electricity when the aqueous phase was the continuous phase.
5. The exact same procedure was followed to obtain phase inversion results for the higher viscosity oil.

As mentioned earlier, five sets of experiments were conducted to study the effects of pure and mixed stabilizers on phase inversion in emulsion systems. The first three sets of experiments were conducted with three pure stabilizers (surfactant, 50% hydrophobic nanoparticles, or 30% hydrophobic nanoparticles) with varying concentrations. The other two sets of experiments dealt with the effect of mixed nanoparticle/surfactant stabilizers on phase inversion in emulsions. In the case of the mixed nanoparticle/surfactant stabilizer, the total combined concentration of the two stabilizers (nanoparticles and surfactant) was held constant at 0.1 wt%. However, the proportion of surfactant (EMSORB 2503) in the mixed stabilizer was varied from 0 to 100 percent. Further details about the experiments conducted using individual stabilizers and the mixed stabilizers are summarized in Tables 3.6 and 3.7:

Table 3.6 *Experiments conducted using individual and mixed stabilizers (Oil Grade - Purity FGWO15)*

INITIAL OIL (gm) (Viscosity: 22.9mPa.s)	**STABILIZER**	**STABILIZER CONCENTRATION (wt% in Oil)**
500	EMSORB 2503	0.004 – 0.1
500	HDK H20	0.05 – 1.0
500	HDK HKS D	0.05 – 3.0
500	EMSORB 2503 + HDK H20	0.1 (total combined concentration)
500	EMSORB 2503 + HDK HKS D	0.1 (total combined concentration)

Table 3.7 Experiments conducted using individual and mixed stabilizers (Oil Grade - Purity FGWO35)

INITIAL OIL (gm) (Viscosity: 64.5mPa.s)	**STABILIZER**	**STABILIZER CONCENTRATION (wt% in Oil)**
500	EMSORB 2503	0.005 – 0.1
500	HDK H20	0.1 – 1.0
500	HDK HKS D	0.1 – 3.0
500	EMSORB 2503 + HDK H20	0.1 (total combined concentration)
500	EMSORB 2503 + HDK HKS D	0.1 (total combined concentration)

3.3.3. Stability Study

In order to investigate the impact of stabilizers on emulsion stability, emulsion samples were collected at a water fraction of $\phi_w = 0.2$ and their stability were studied as described below:

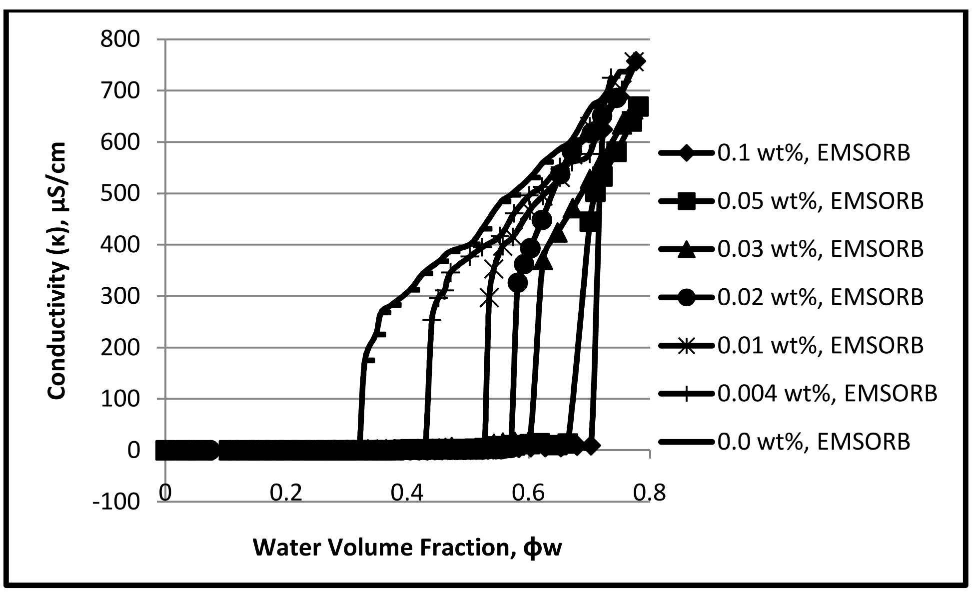
1. The samples were dispensed in 10ml glass vials and images were captured at regular time intervals (30 seconds to 2 hours) using Nikon 5200, 5 MP digital camera.
2. The de-stabilization trends were studied by observing the sedimentation of emulsions (settling of the aqueous phase at the bottom of the emulsion) stabilized with different stabilizers.
3. In order to obtain quantitative results, 100ml samples of different emulsions were obtained in graduated cylinders and the coalescence of aqueous phase at the bottom was monitored with respect to time

Chapter 4. EXPERIMENTAL RESULTS

This chapter consists of four sections. In section 4.1, experimental results for emulsions stabilized with surfactant (EMSORB 2503) alone are described. In section 4.2, experimental results for emulsions stabilized with silica nanoparticles are described. Section 4.3 describes the experimental results for emulsions stabilized with mixed stabilizers. The last section (section 4.4) deals with experimental results on the stability of emulsions.

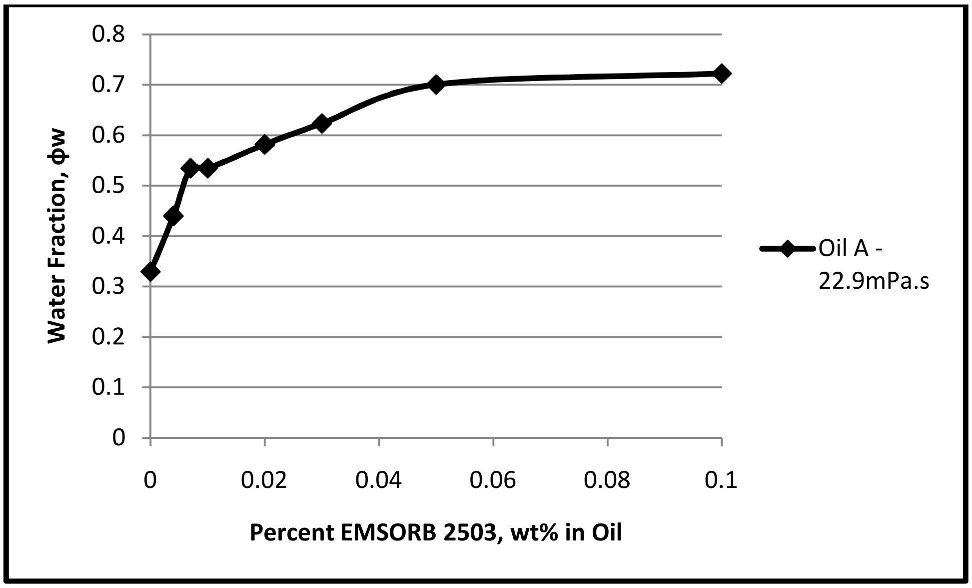
4.1. Pure Surfactant as Stabilizer

Figure 4.1 shows the conductivity plots for emulsions stabilized with pure surfactant (EMSORB 2503). The surfactant concentration in the oil phase (Oil A of viscosity 22.9mPa.s) was varied from 0.004 wt% to 0.1 wt%. With the increase in water volume fraction, the conductivity remained negligibly small until the phase inversion point.



<u>Figure 4.1</u> Conductivity data for emulsions stabilized with EMSORB 2503 at different surfactant concentrations (Oil A, Viscosity – 22.9mPa.s)

Upon inversion of water-in-oil (W/O) emulsion to oil-in-water (O/W) emulsion, a sharp increase in the conductivity occurred. As shown in Figure 4.2, the phase inversion point was delayed to higher water concentrations by increasing the surfactant concentration in the oil phase. The phase inversion point shifts from about 32 vol. % to over 70 vol. % water upon increasing the surfactant concentration from 0 to 0.1 wt%.



<u>Figure 4.2</u> Phase Inversion concentration of water as a function of surfactant (EMSORB 2503) concentration (Oil A, Viscosity – 22.9mPa.s)

Figure 4.3 shows the conductivity plots for surfactant stabilized emulsions prepared from the higher viscosity oil (Oil B, viscosity 64.5mPa.s). Trends similar to lower viscosity oil are observed for the higher viscosity oil. Increasing the surfactant concentration raises the phase inversion concentration. However, in comparison to the lower viscosity oil, the phase inversion concentrations are lower for the higher viscosity oil (see Figure 4.4).

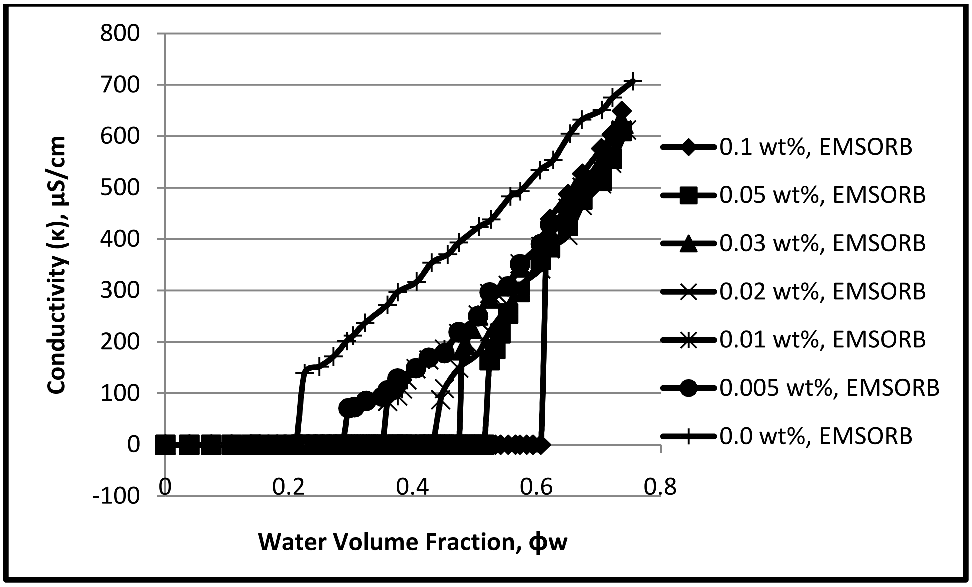


Figure 4.3 Conductivity data for emulsions stabilized using EMSORB 2503 at different surfactant concentrations (Oil B, Viscosity – 64.5mPa.s)

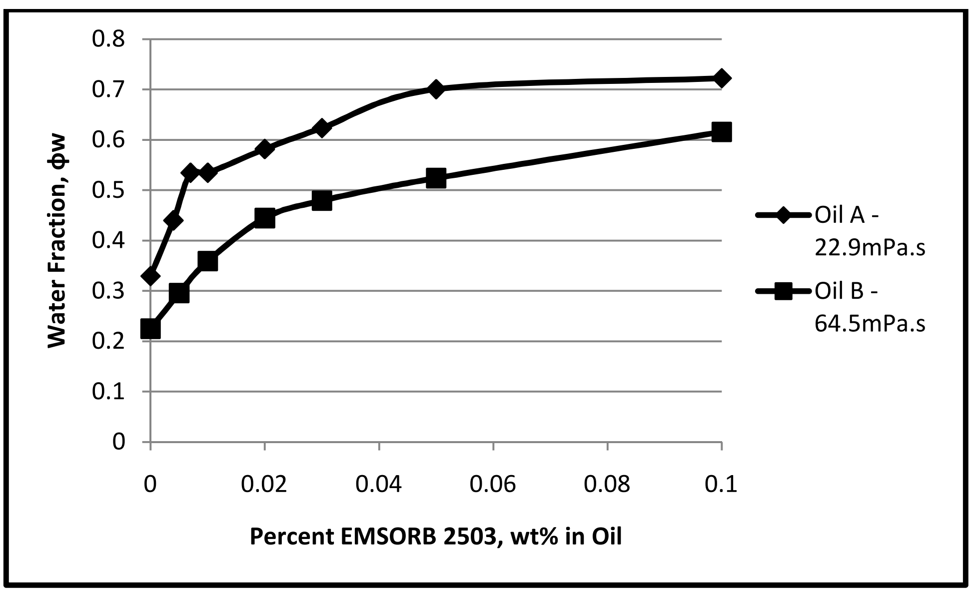


Figure 4.4 Phase inversion concentration of water as a function of surfactant (EMSORB 2503) concentrations for oils A and B

4.2. Silica Nanoparticles as Stabilizers

4.2.1. 50% Hydrophobic Nanoparticles

Figure 4.5 shows the conductivity plots for emulsions stabilized with 50% hydrophobic nanoparticles (HDK H20). The concentration of the nanoparticles was varied from 0.05 wt% to 1.0 wt% based on the oil phase (Oil A). As expected, a sharp increase in the conductivity occurs upon inversion of water-in-oil (W/O) emulsion to oil-in-water (O/W) emulsion.

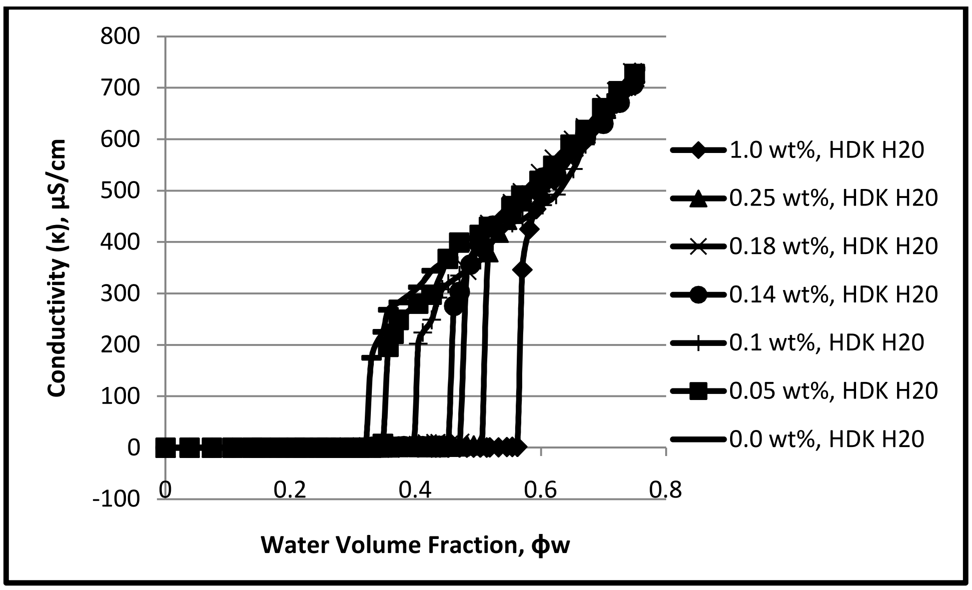


Figure 4.5 Conductivity data for emulsions stabilized with HDK H20 at different solids (HDK H20) concentrations (Oil A, Viscosity – 22.9mPa.s)

From Figure 4.6, it is clear that the water volume fraction where phase inversion takes place increases with the increase in the nanoparticle concentration. However, it is important to note that in the present case of nanoparticle stabilizer, a significantly higher stabilizer concentration is required to achieve the same phase inversion concentration as attained in the pure surfactant case (see Figure 4.2).

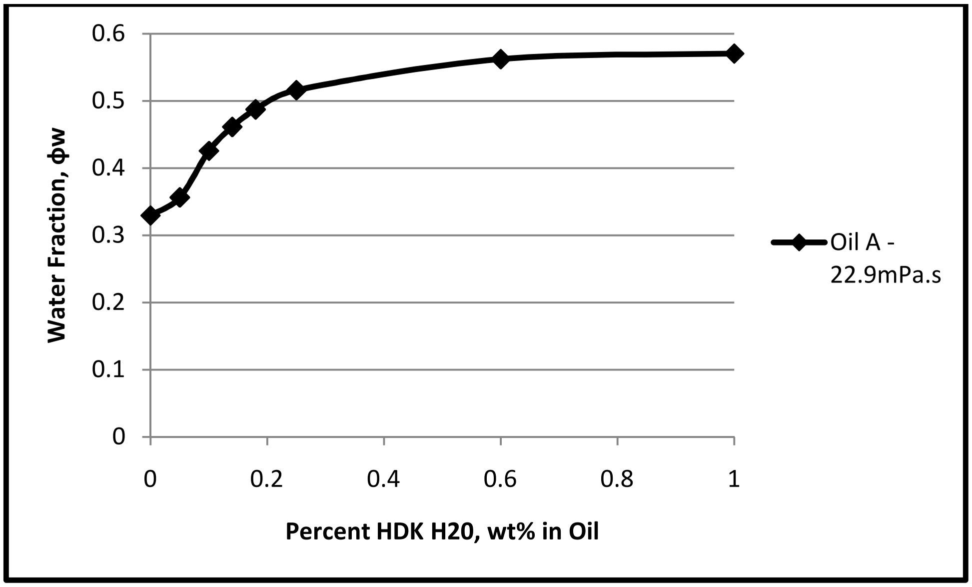


Figure 4.6 *Phase Inversion concentrations of water as a function of solids (HDK H20) concentration (Oil A, Viscosity – 22.9mPa.s)*

For the higher viscosity oil (Oil B), the phase inversion concentrations were lower than those of oil A up to a silica concentration of 0.3 wt%. However, at higher silica concentrations the opposite trend was observed (see Figures 4.7 and 4.8).

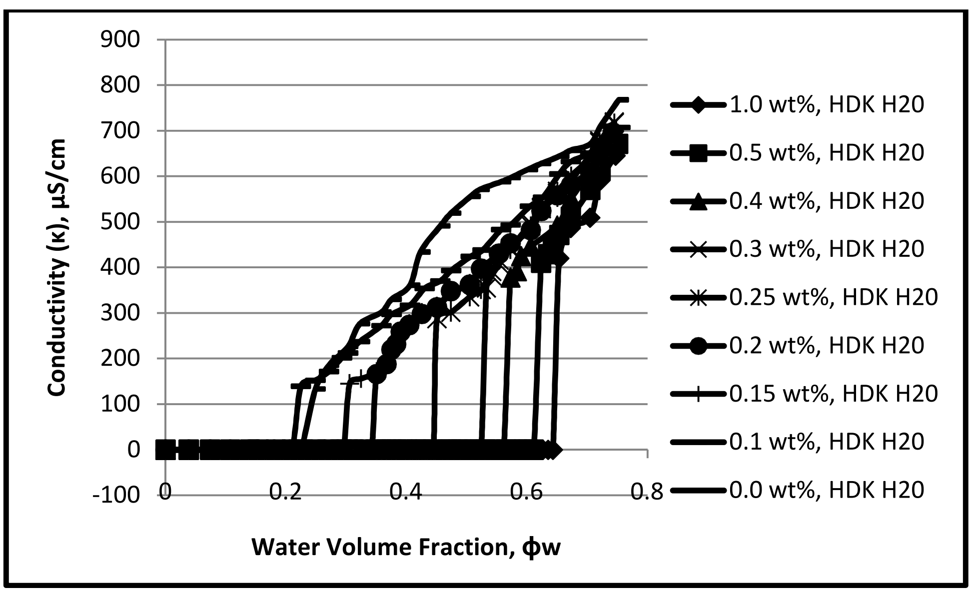


Figure 4.7 *Conductivity data for emulsions stabilized with HDK H20 at different solids (HDK H20) concentrations (Oil B, Viscosity – 64.5mPa.s)*

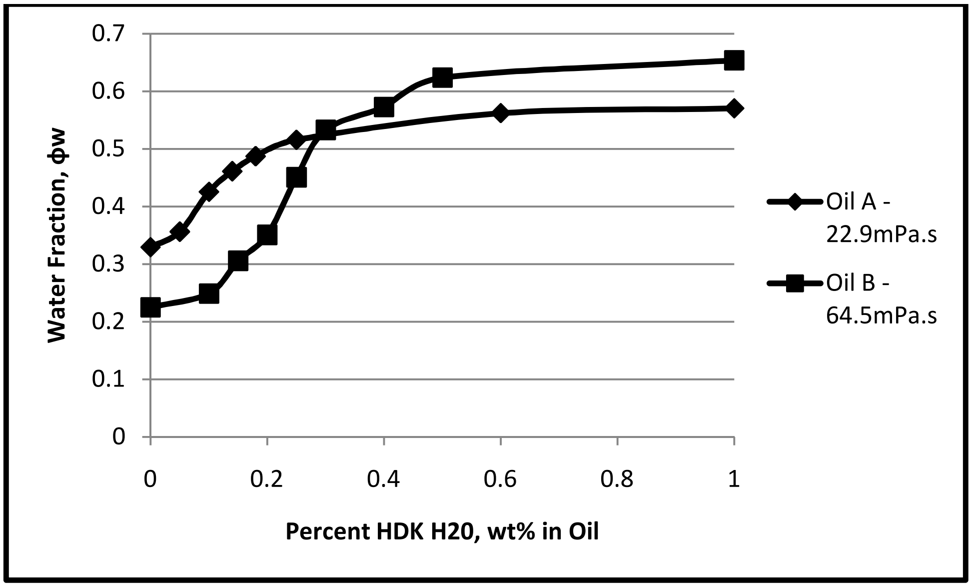
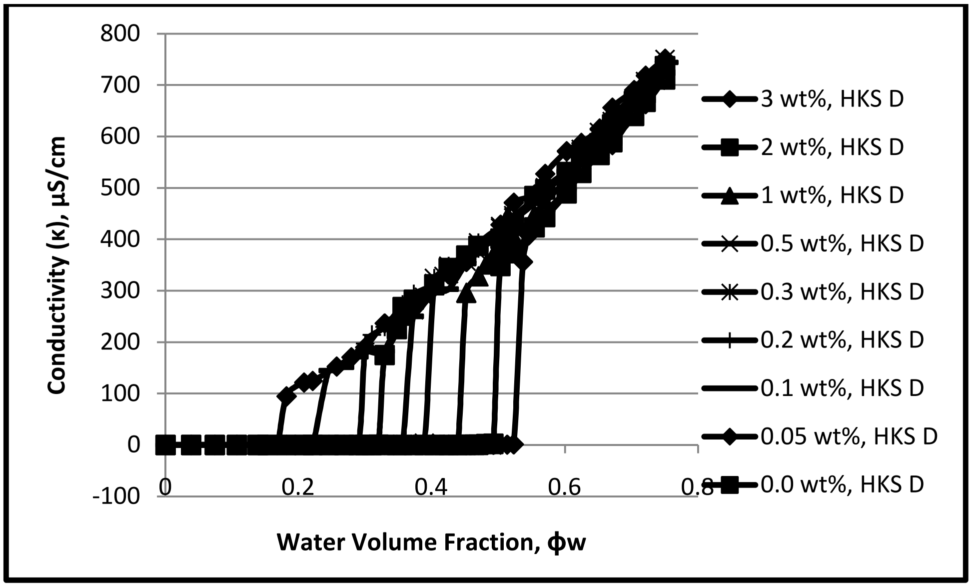


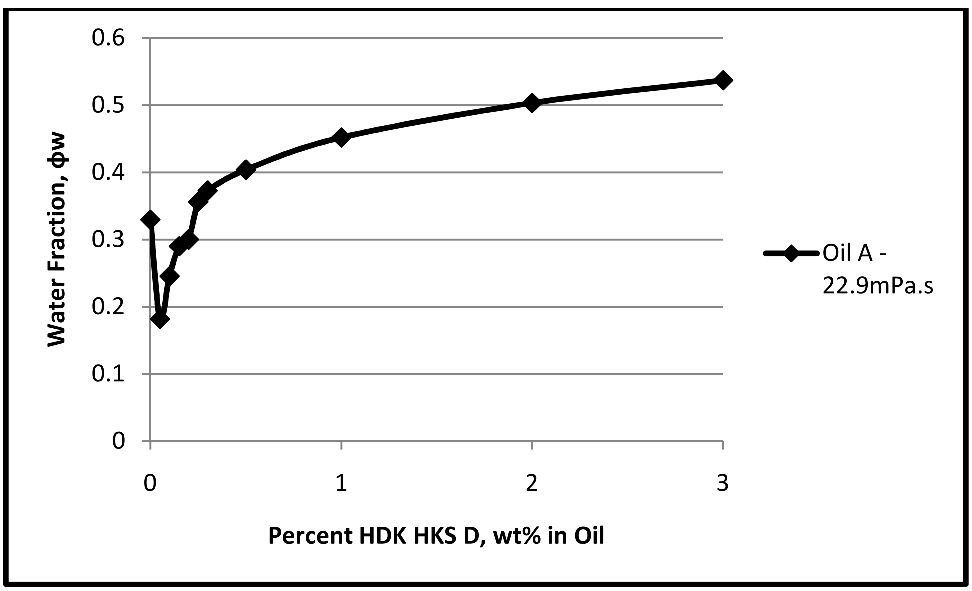
Figure 4.8 Phase inversion concentration of water as a function of HDK H20 concentrations for oils A and B

4.2.2. 30% Hydrophobic Nanoparticles

To investigate the effect of hydrophobicity of nanoparticles, silica nanoparticles of 30% SiOH content (HDK HKS D) were used to stabilize the emulsions. The particle concentration was varied from 0.1 wt% to 3.0 wt% in the oil phase (Oil A). The phase inversion concentration of water initially decreased and then increased with the increase in the nanoparticle concentration (see Figures 4.9 and 4.10).



<u>Figure 4.9</u> Conductivity data for emulsions stabilized with HDK HKS D at different solids (HDK HKS D) concentrations (Oil A, Viscosity – 22.9mPa.s)



<u>Figure 4.10</u> Phase Inversion concentration of water as a function of HDK HKS D concentration (Oil A, Viscosity – 22.9mPa.s)

It is important to note that phase inversions in the present case of 30% hydrophobic nanoparticles occurs at a lower water concentration when comparison is made with the more hydrophobic grade (50% hydrophobicity) nanoparticles at the same solids concentration.

Similar trends were exhibited by emulsions prepared from the higher viscosity oil (Oil B) and stabilized by 30% hydrophobic nanoparticles (HKS D). The conductivity plots showing phase inversion of W/O system to O/W system for HKS D stabilized emulsions prepared from oil B are shown in Figure 4.11. The water volume fraction at which inversion occurs is slightly lower in the case of high viscosity oil when comparison is made with the data for lower viscosity oil (See Figure 4.12).

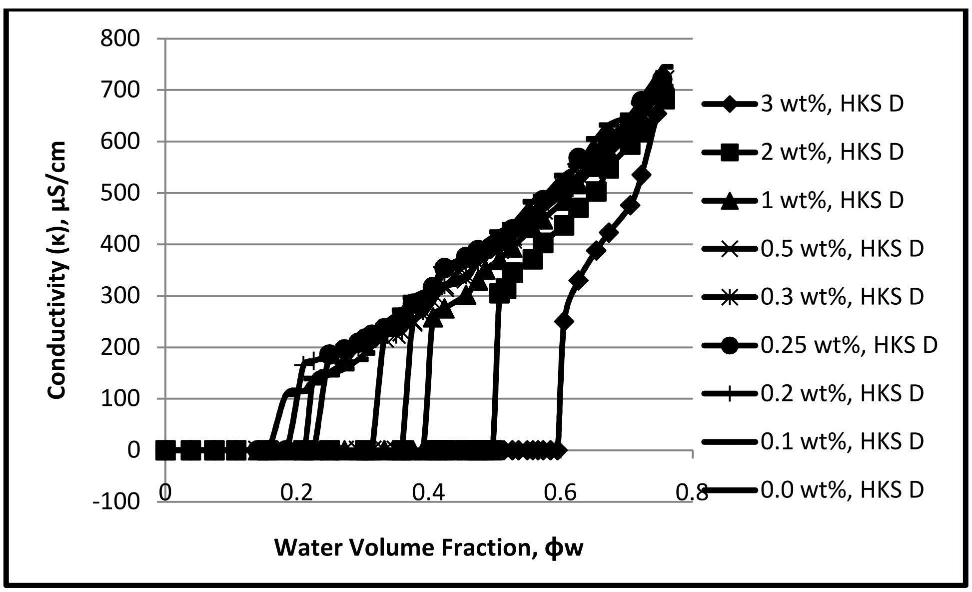


Figure 4.11 Conductivity data for emulsions stabilized with HDK HKS D at different solids (HDK HKS D) concentrations (Oil B, Viscosity – 64.5mPa.s)

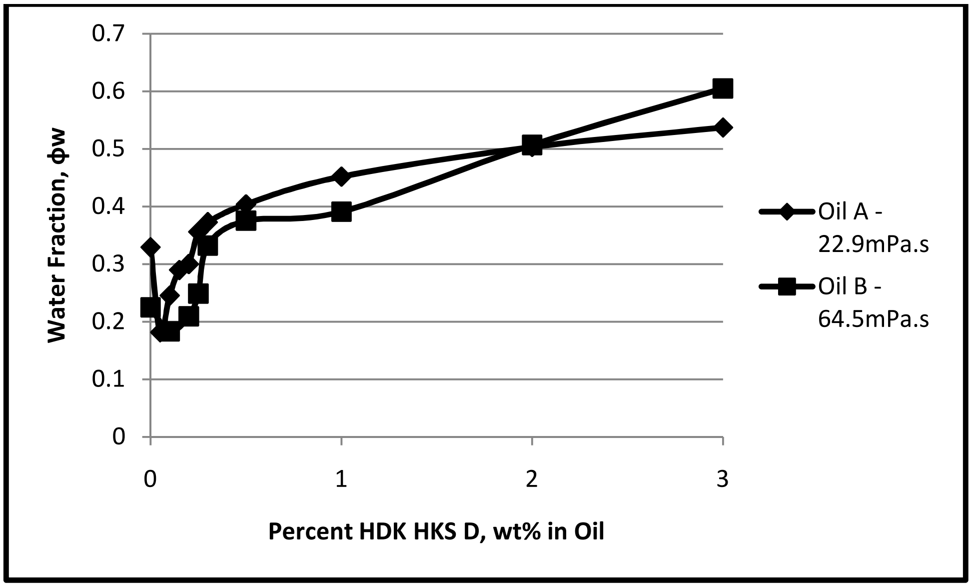
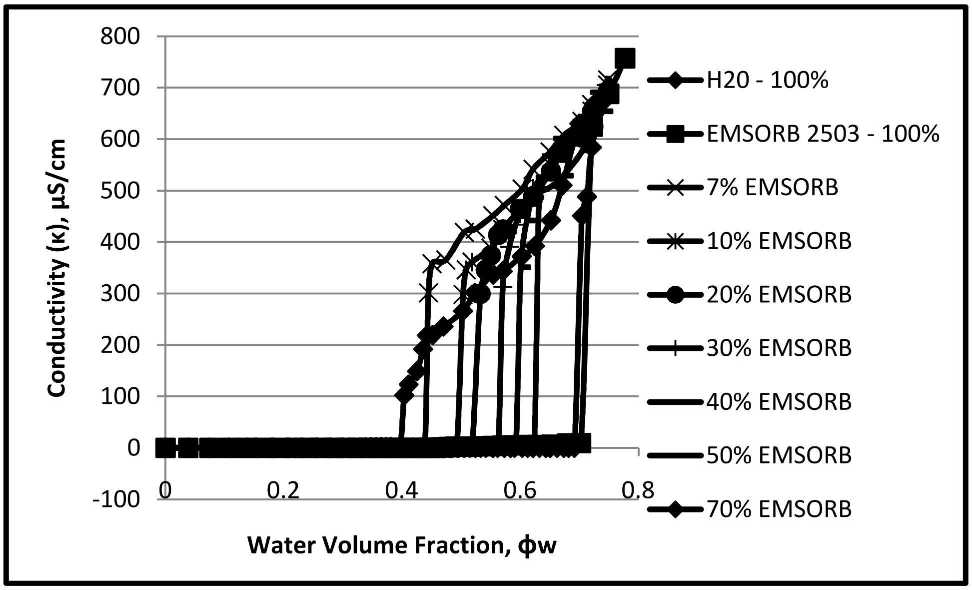


Figure 4.12 *Phase inversion concentration of water as a function of HDK HKS D concentration for oils A and B*

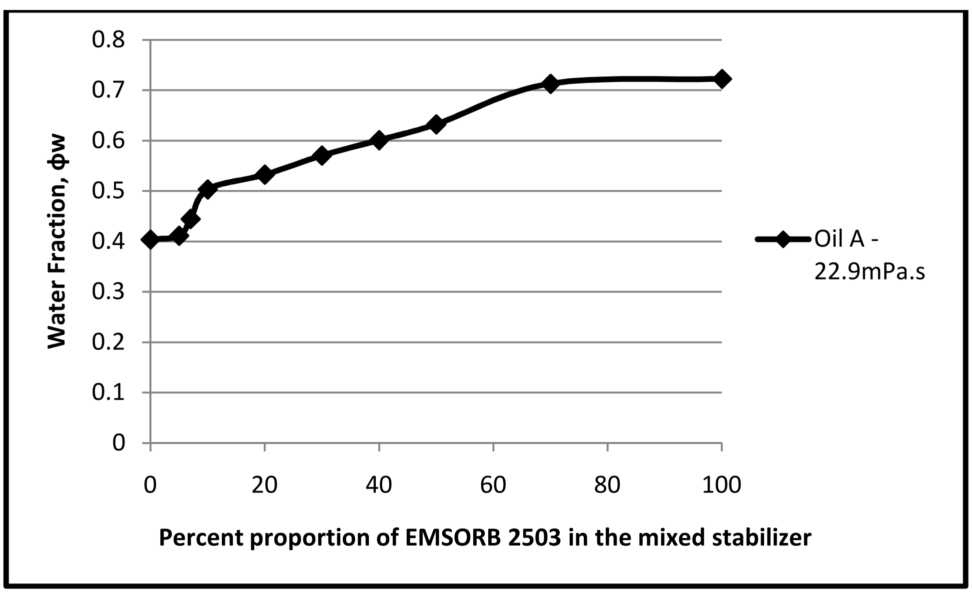
4.3. Mixed Surfactant/Nanoparticles as Stabilizer

4.3.1. Surfactant and 50% Hydrophobic Nanoparticles

For the mixed surfactant/nanoparticles experiments, the first set of experiments were conducted with EMSORB 2503 and 50% hydrophobic grade (HDK H20) silica nanoparticles. The total concentration of the mixed stabilizer was fixed at 0.1 wt% in oil but the composition of the mixed stabilizer was varied from 0 to 100 % surfactant. Figures 4.13 and 4.14 show that with increasing the proportion of surfactant in the mixed stabilizer, the water volume fraction at which phase inversion occurs also increases. This clearly demonstrates that the surfactant is much more effective than nanoparticles in delaying the phase inversion of W/O emulsion to O/W emulsion.

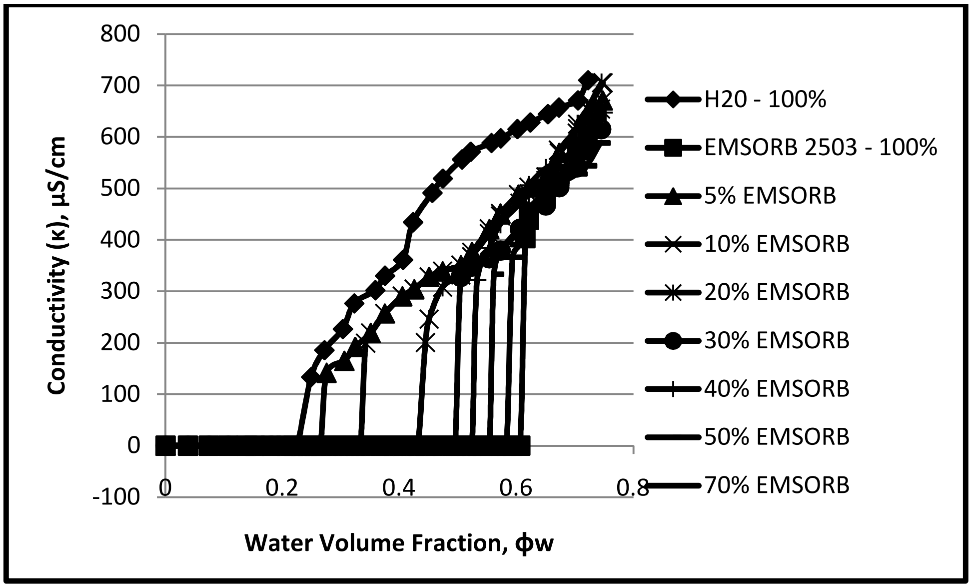


<u>Figure 4.13</u> Conductivity data for emulsions stabilized with mixed stabilizers: EMSORB 2503 and HDK H20. The data are monitored for increasing EMSORB proportion in the mixed stabilizer (Oil A, Viscosity – 22.9mPa.s)

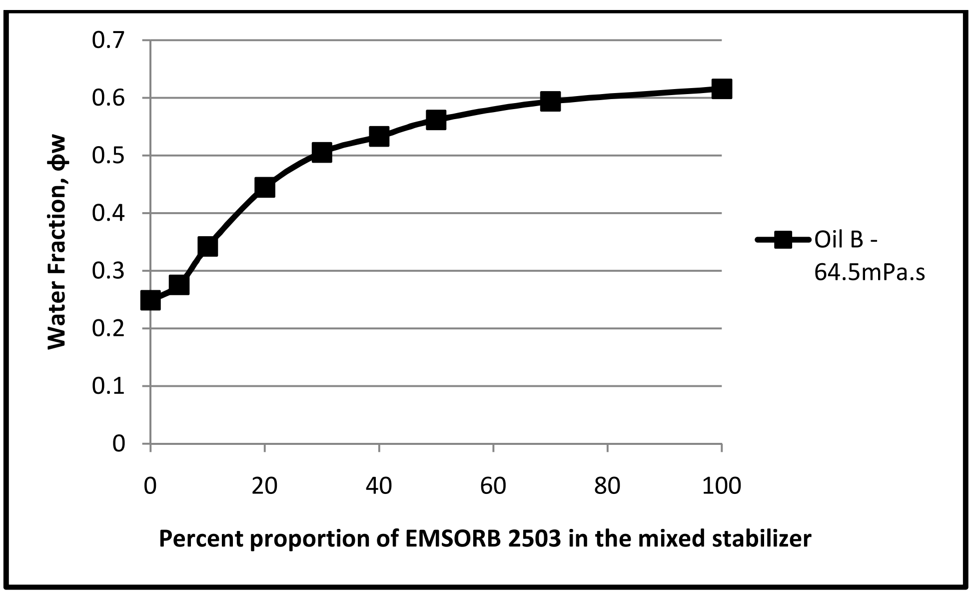


<u>Figure 4.14</u> Phase Inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer (Oil A, Viscosity – 22.9mPa.s)

Figures 4.15 and 4.16 show the phase inversion data for emulsions prepared from higher viscosity oil (Oil B).



<u>Figure 4.15</u> Conductivity data for emulsions stabilized with mixed stabilizers: EMSORB 2503 and HDK H20. The data are monitored for increasing EMSORB proportion in the mixed stabilizer (Oil B, Viscosity – 64.5mPa.s)



<u>Figure 4.16</u> Phase Inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer (Oil B, Viscosity – 64.5mPa.s)

For oil B of viscosity 64.5mPa.s, the water volume fraction at which phase inversion takes place from W/O to O/W emulsion is much lower. This can be seen clearly in Figure 4.17.

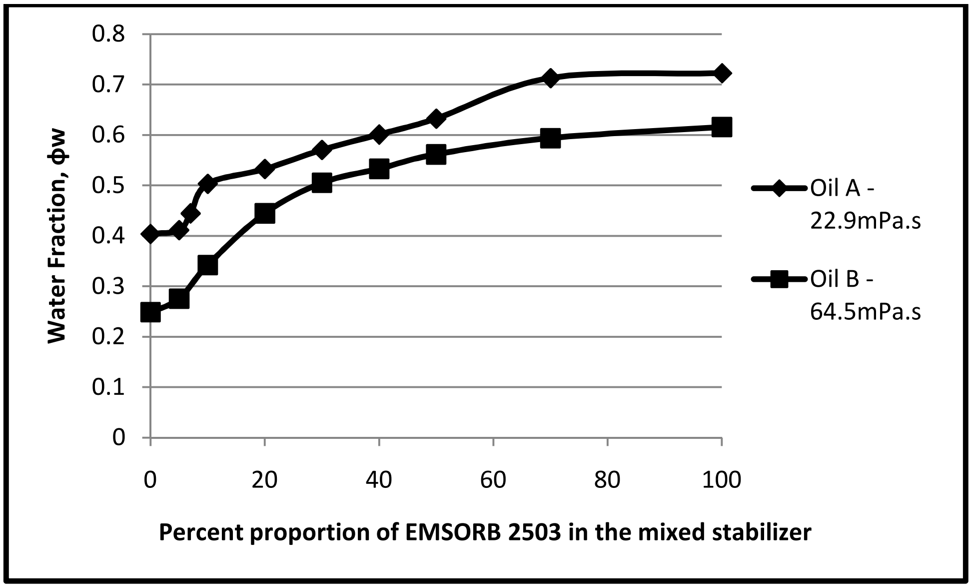


Figure 4.17 Phase inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer for oils A and B

4.3.2. Surfactant and 30% Hydrophobic Nanoparticles

The second set of experiments were conducted with the mixed surfactant/nanoparticles consisting of EMSORB 2503 and 30% hydrophobic grade (HDK HKS D) silica nanoparticles. According to the plots shown in Figures 4.18 and 4.19, the behaviour of this mixed surfactant/nanoparticles system is similar to that of the earlier system (Figures 4.13 and 4.14) indicating that the surfactant is more effective than nanoparticles in delaying the phase inversion point.

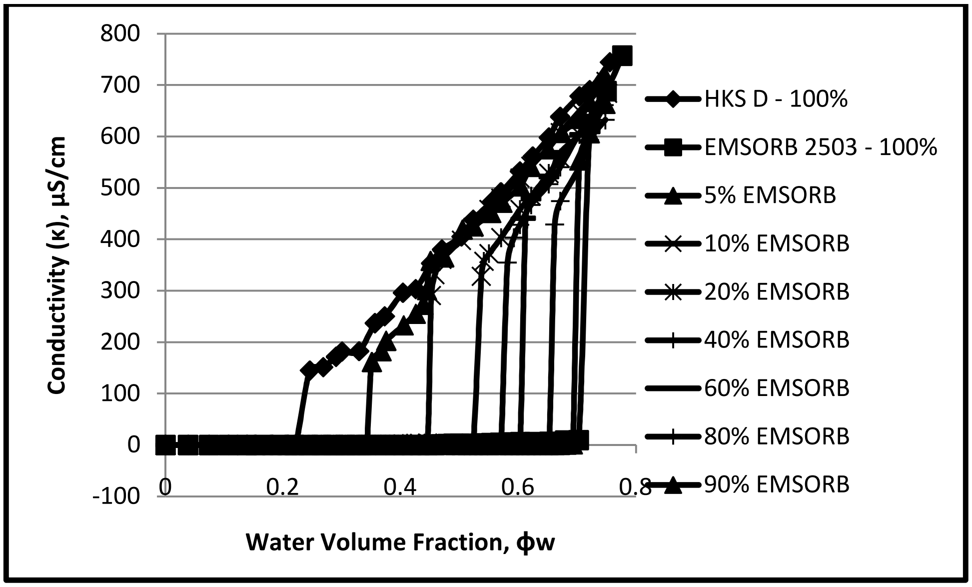


Figure 4.18 *Conductivity data for emulsions stabilized with mixed stabilizers: EMSORB 2503 and HDK HKS D. The data are monitored for increasing EMSORB proportion in the mixed stabilizer (Oil A, Viscosity – 22.9mPa.s)*

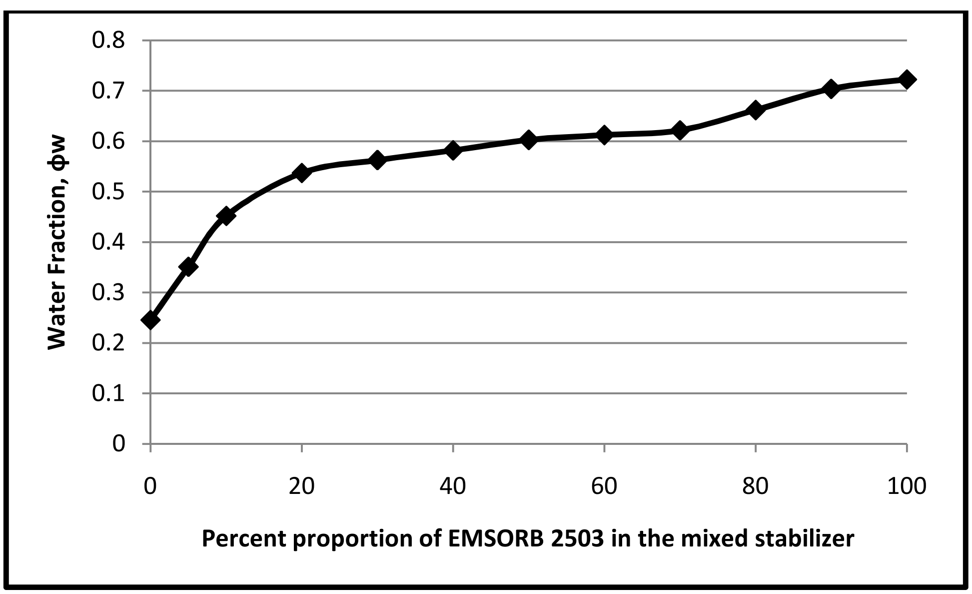
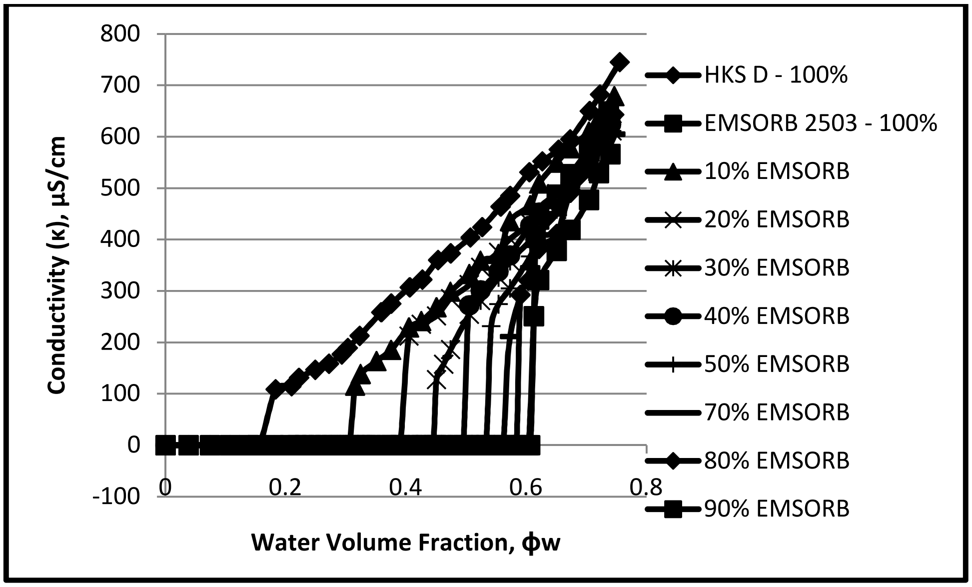
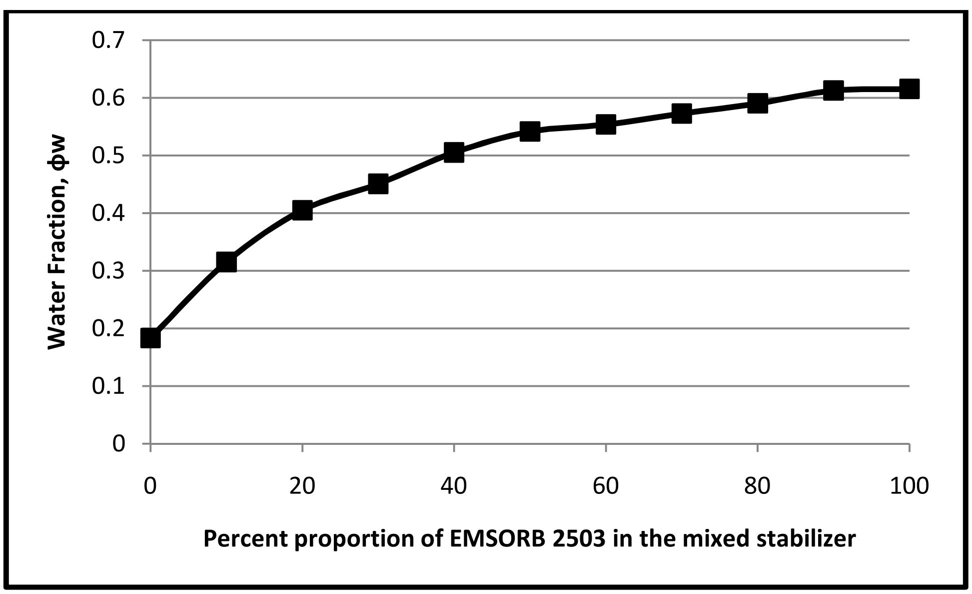


Figure 4.19 *Phase Inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer (Oil A, Viscosity – 22.9mPa.s)*

Figures 4.20 and 4.21 show the data for the higher viscosity oil (Oil B of viscosity 64.5mPa.s). The trends observed for the higher viscosity oil are similar to those observed for the lower viscosity oil.



<u>Figure 4.20</u> Conductivity data for emulsions stabilized with mixed stabilizers: EMSORB 2503 and HDK HKS D. The data are monitored for increasing EMSORB proportion in the mixed stabilizer (Oil B, Viscosity – 64.5mPa.s)



<u>Figure 4.21</u> Phase Inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer (Oil B, Viscosity – 64.5mPa.s)

However, the phase inversion concentration of water is lower for the higher viscosity oil (see Figure 4.22).

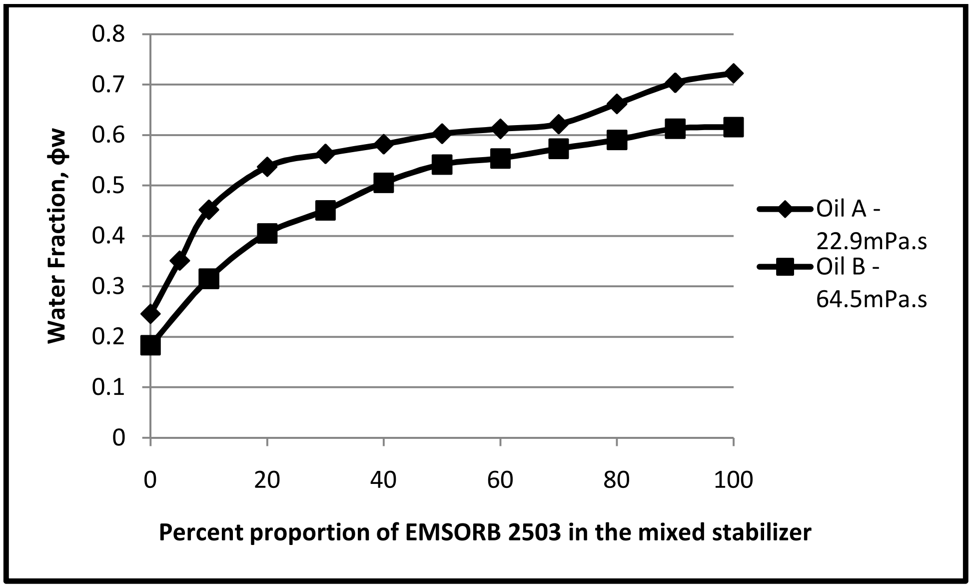


Figure 4.22 Phase inversion concentration of water as a function of EMSORB 2503 proportion in the mixed stabilizer for oils A and B

4.4. Stability Study of Emulsions stabilized with Individual and mixed stabilizers

Emulsion stability was examined for emulsions prepared from oil A (Viscosity 22.9 mPa.s) using individual and mixed stabilizers. Emulsions were prepared using different concentrations of surfactant, silica nanoparticles, and combination of the two stabilizers. Samples of W/O emulsions containing 20% of the dispersed phase (water) were observed and pictures were taken at different time intervals to study the effect of coalescence of the dispersed phase that eventually settled down at the bottom of the sample.

Figures 4.23 (a)-(c) show the images of the emulsion samples prepared from single stabilizers. The figures reveal that the emulsion stabilized using the surfactant alone separates faster than the emulsions prepared using silica nanoparticles as the sole stabilizers. After a one minute mark, no separation takes place in any of the systems.

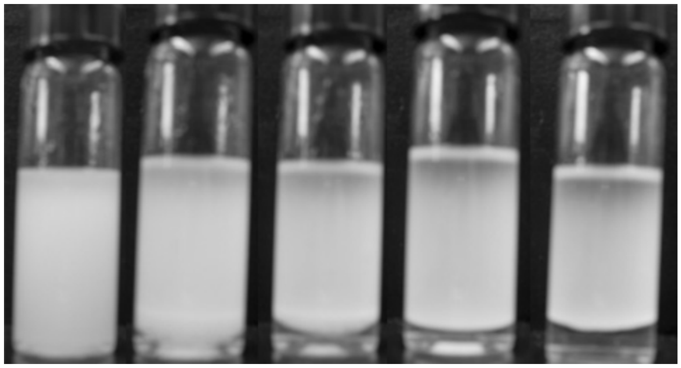


Figure 4.23a) *Emulsions prepared using EMSORB 2503 as a lone stabilizer. EMSORB 2503 concentration = 0.1 wt% in oil. All samples were collected at $\phi_w = 0.2$ and monitored for time intervals at 1, 5, 15, 30, and 60 minute mark*

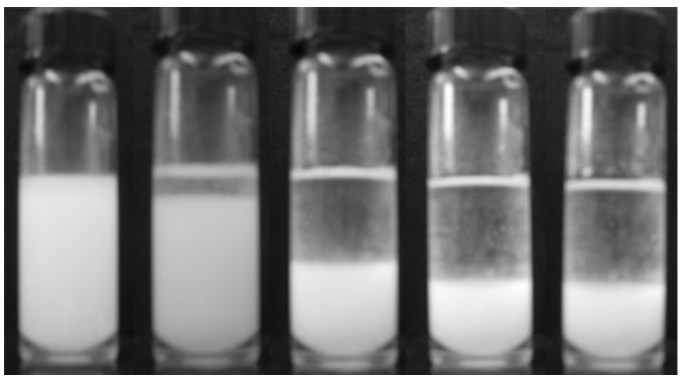


Figure 4.23b) *Emulsions prepared using HDK H20 as a lone stabilizer. HDK H20 concentration = 0.1 wt% in oil. All samples were collected at $\phi_w = 0.2$ and monitored for time intervals at 1, 5, 15, 30, and 60 minute mark*

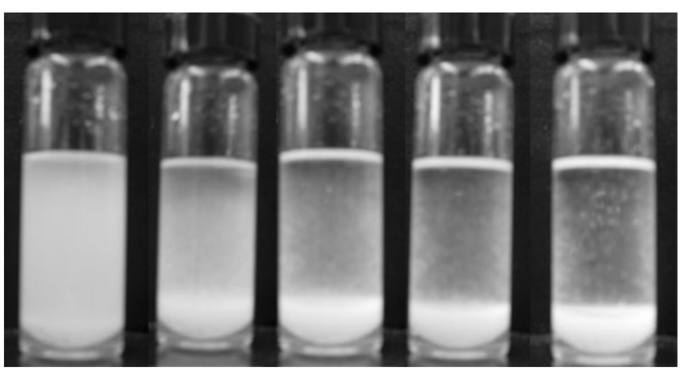
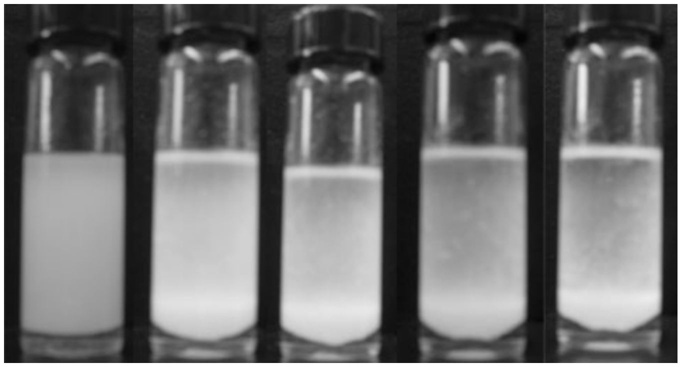
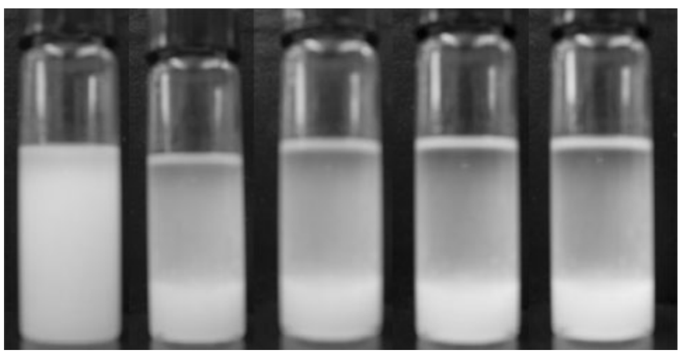


Figure 4.23c) *Emulsions prepared using HDK HKS D as a lone stabilizer. HDK HKS D concentration = 0.1 wt% in oil. All samples were collected at $\phi_w = 0.2$ and monitored for time intervals at 1, 5, 15, 30, and 60 minute mark*

However, during the course of time there occurs a significant separation of water at the bottom of the emulsion sample for the emulsion stabilized with surfactant alone (Figure 4.23a). It should also be noticed that emulsions stabilized using silica nanoparticles hardly show any separation of the dispersed aqueous phase (see Figure 4.23(b)-(c)).



a) Emulsions prepared using mixed stabilizers (1:1 ratio of EMSORB to HDK HKS D). Total stabilizer concentration was constant at 0.1 wt%.

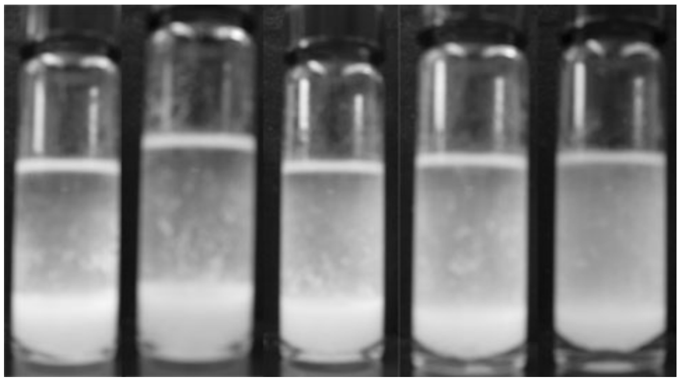


b) Emulsions prepared using mixed stabilizers (1:1 ratio of EMSORB to HDK H20). Total stabilizer concentration was constant at 0.1 wt%.

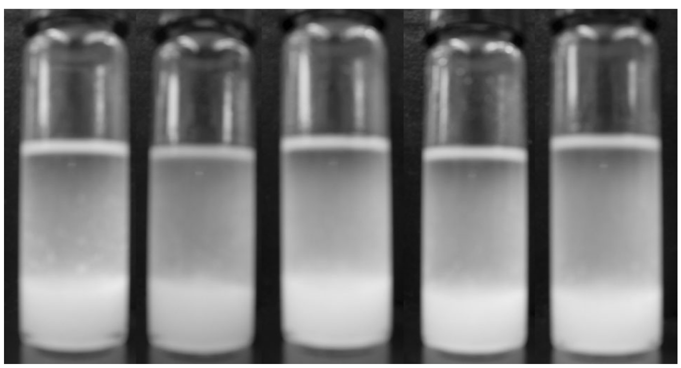
Figure 4.24 Emulsions stabilized using mixed stabilizers. All samples were collected at $\phi_w = 0.2$ and monitored for time intervals at 1, 5, 15, 30, and 60 minute mark

Figure 4.24 shows the images of the emulsion samples prepared from mixed stabilizers, EMSORB 2503 and nanoparticles, in the ratio of 1:1 at a total stabilizer concentration of 0.1 wt% based on oil. It can be seen from Figure 4.24 that by using a more hydrophobic grade of silica nanoparticles, a more stable emulsion is formed. Emulsion stabilized with 50% hydrophobic nanoparticles (HDK H20) shows no significant separation compared to the emulsion stabilized with 30% hydrophobic particles (HDK HKS D).

Figure 4.25 shows the images of the emulsion samples prepared from mixed stabilizer (total concentration = 0.1 wt% based on oil) with varying proportions of surfactant in the mixed stabilizer. The images are taken after a fixed time interval of 60 minutes. With increasing proportion of surfactant in the mixed stabilizer, separation of water tends to become faster especially for HDK HKS D nanoparticles.



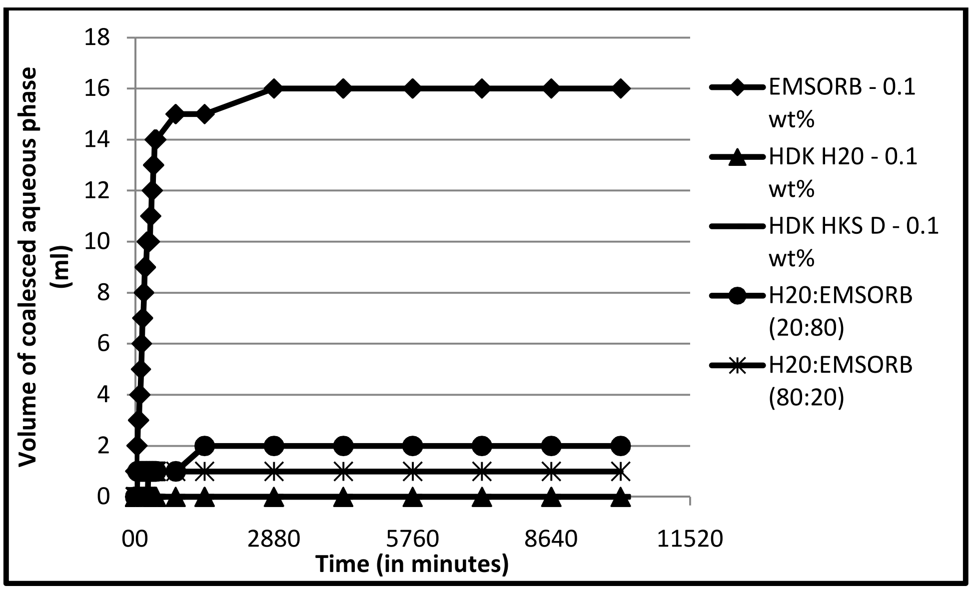
a) Emulsions prepared using mixed stabilizers (HKS D and EMSORB) with increasing surfactant proportion. Total stabilizer concentration was constant at 0.1 wt%. Surfactant proportion starts at 10% and goes to 50% with increasing intervals of 10%.



b) Emulsions prepared using mixed stabilizers (H20 and EMSORB) with increasing surfactant proportion. Total stabilizer concentration was constant at 0.1 wt%. Surfactant proportion starts at 10% and goes to 50% with increasing intervals of 10%.

Figure 4.25 Emulsions stabilized using mixed stabilizers with increasing surfactant composition. All samples were collected at $\phi_w = 0.2$ and monitored at the 60 minute mark

These results are further confirmed by the data shown in Figure 4.26 where the volume of aqueous phase separated from the emulsion sample (100 ml) is plotted as a function of time. Emulsion stabilized by surfactant alone (0.1 wt% based on oil) shows a high separation of water whereas emulsions stabilized by nanoparticles alone show little separation. With the increasing proportion of surfactant in the mixed stabilizer, the separation of water increases. However, the degree of separation of water is small in the presence of silica nanoparticles as partial stabilizers. For silica nanoparticles to surfactant ratio of 20:80 a separation of about 2 ml of water is seen at the bottom of the emulsion, and for 80:20 ratio of nanoparticles to surfactant, only about 1 ml of water separation is observed.



<u>Figure 4.26</u> Volume of coalesced aqueous phase for emulsions stabilized using individual and mixed stabilizers

Chapter 5. DISCUSSION

The emulsion morphology (either water-in-oil or oil-in-water) and the phase inversion phenomenon depend on three variables: formulation, composition, and protocol variables [29]. *Formulation variables* are independent of the quantity and are characterized based on the individual phase properties as well as nature of the stabilizing components. *Composition variables*, on the other hand, are quantitative variables such as the concentration of stabilizer and the volume fractions of the two phases. Finally, *protocol variables* define the conditions under which the emulsion is formed, such as homogenizing speed, type of vessel used to form the emulsion etc.

In our study, we have focused mainly on the effects of formulation and composition variables on phase inversion phenomenon and stability of emulsions. The formulation variables investigated in this study include the type of stabilizer used (surfactant, nanoparticles, or their mixture) the hydrophobicity of silica nanoparticles and the viscosity of oil used.

The composition variables investigated are: surfactant concentration and the volume fractions of the two phases. The protocol variables are kept constant throughout the experimental work.

5.1. Effect of dispersed phase volume fraction on stability and phase inversion

In our work, oil containing the stabilizer was the continuous phase at the start of the experimental runs. The dispersed phase was an aqueous solution consisting of 0.01 M NaCl. With the increase in the dispersed phase concentration and due to the presence of the homogenizing effect, the number of dispersed phase droplets is increased.

Near the phase inversion point, the aqueous phase droplets touch each other trapping the oil phase. At the phase inversion point, coalescence of aqueous droplets takes place thereby inverting the emulsion system. Hence, the emulsion that started off as a water-in-oil (W/O) emulsion is now in the oil-in-water (O/W) emulsion form [29, 30].

The above mechanism is shown schematically in Figure 5.1.

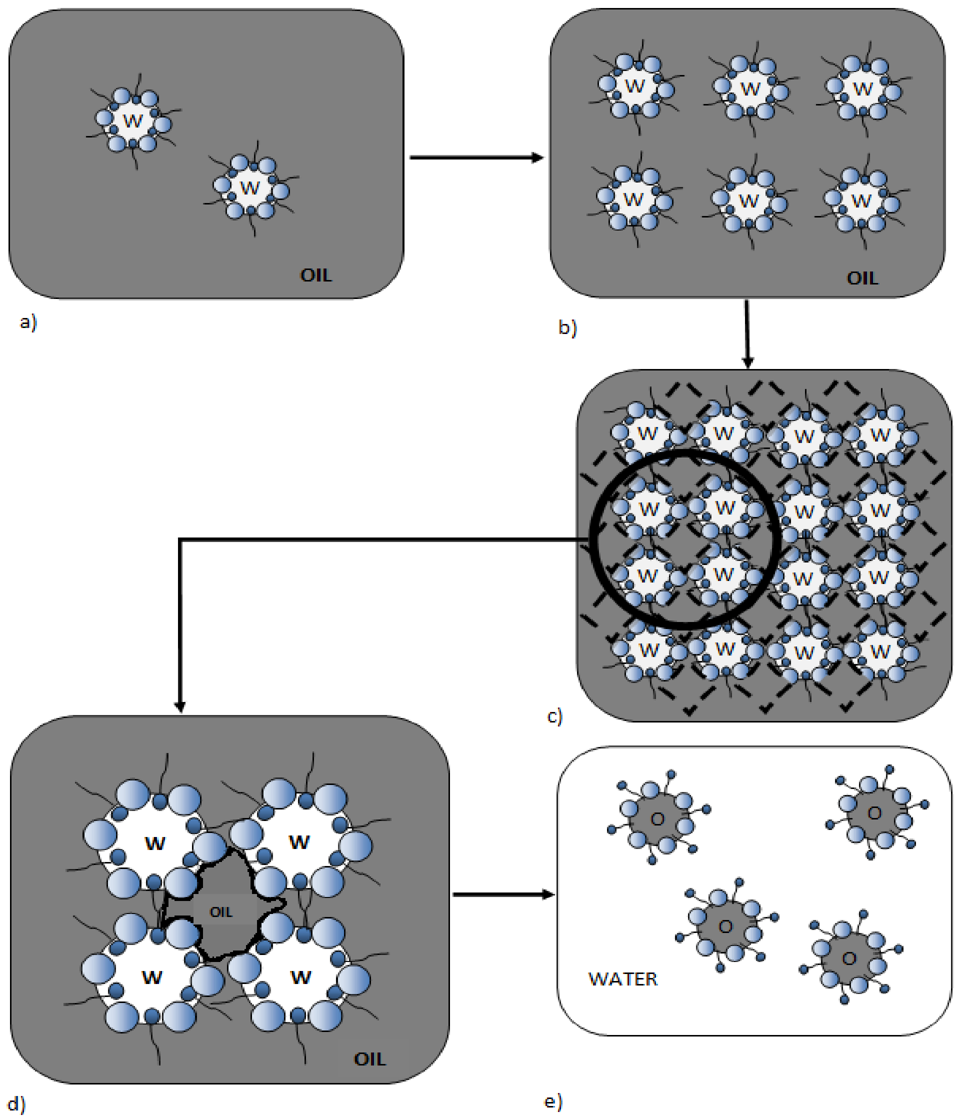


Figure 5.1 a) Initially water is dispersed in oil forming W/O emulsion with hydrophobic tails of surfactant pointing towards oil and polar heads facing the water b) Addition of water increases the number of water droplets c) Oil is trapped in between the water droplets d) magnified image showing entrapment of oil e) Eventually, phase inversion takes place reversing the surfactant orientation

5.2. Effect of stabilizer on stability and phase inversion

Upon addition of dispersed phase to the continuous phase (containing surfactant), the surfactant molecules align themselves at the interface of the droplets with the hydrophobic tail pointing towards the oil-continuous phase and the hydrophilic head submerged in the aqueous phase. Figure 5.2 shows a depiction of the water-in-oil system and Figure 5.3 shows the oil-in-water system. The presence of the surfactant layer at the interface of the droplets inhibits the coalescence process and as a result, the phase inversion point is shifted to a higher dispersed phase volume fraction (see Figure 4.2).

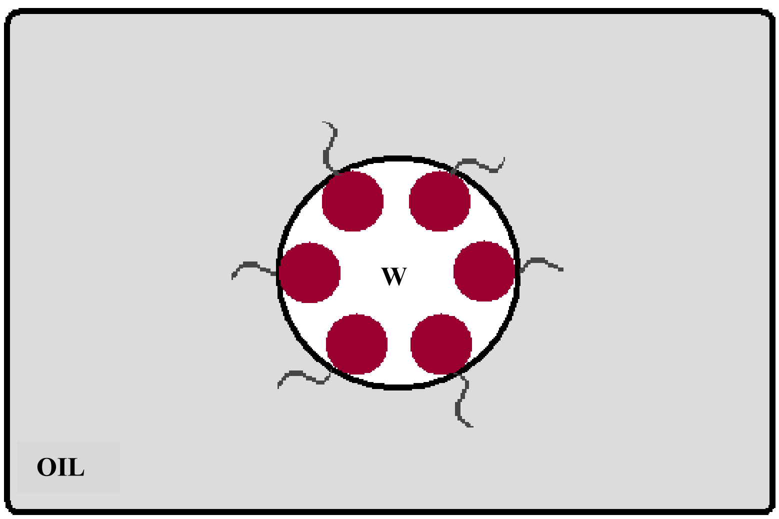


Figure 5.2 *Water in Oil emulsion with the hydrophobic end of the surfactant molecule pointing towards the oil and the hydrophilic head submerged in the non-aqueous phase*

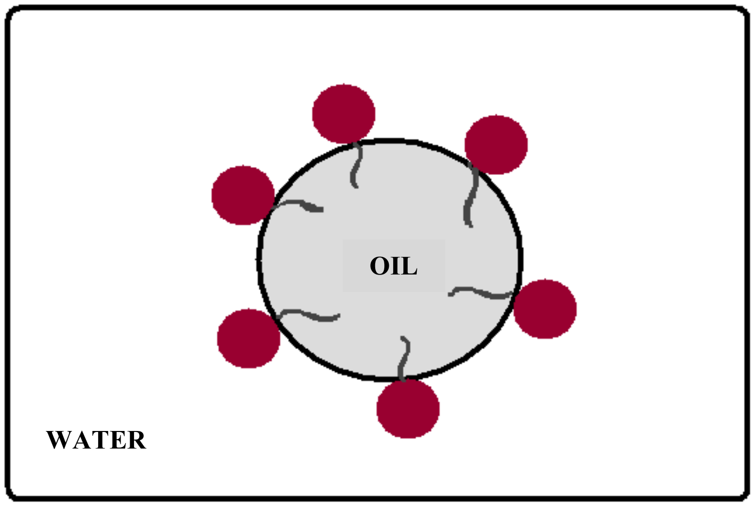


Figure 5.3 Oil in Water emulsion with the hydrophobic end of the surfactant molecule concentrating at the non-polar core and the hydrophilic head surrounding the water phase

The silica nanoparticles used in this work are ampiphilic in nature and it is their wetting ability at the oil-water interface that determines the stability and the phase inversion point of emulsion. Emulsions stabilized using silica nanoparticles allow the nanoparticles to settle at the oil-water interface forming a contact angle between the particles and the oil-water interface as described in Figure 5.4.

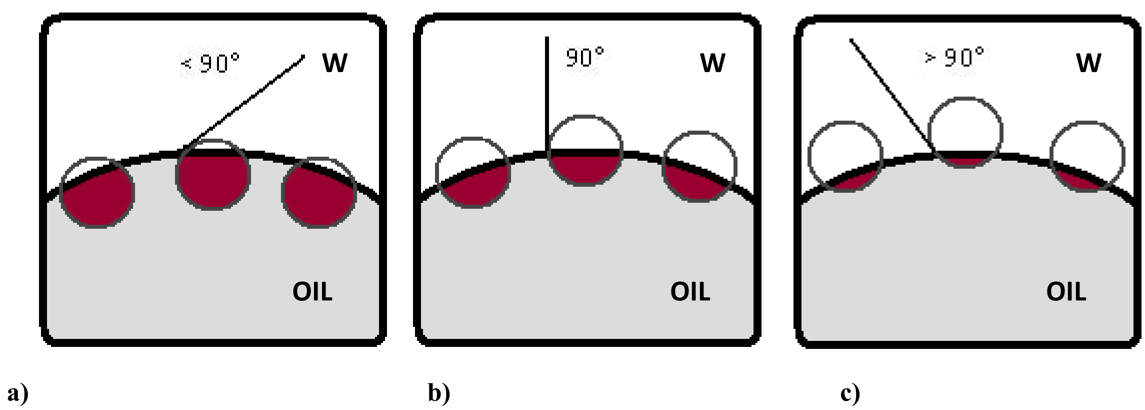


Figure 5.4 a) Ampiphilic Silica Nanoparticle with high hydrophobicity with contact angle < 90°, promoting enhanced wetting of nanoparticles by the oil phase b) Silica Nanoparticle with 50% hydrophobicity forming a 90° contact angle c) Low hydrophobic nanoparticle forming a contact angle > 90°, forming unstable emulsions due to reduced wetting of nanoparticles by the oil phase

The contact angle formation between the oil-nanoparticle-water determines how stable the emulsion will be. It is likely that due to the high hydrophobicity of the nanoparticles, the contact angle formation between the nanoparticle and oil-water interface is much smaller than 90°. In such a case, the nanoparticles are preferentially wetted by the oil phase resulting in stable water-in-oil emulsions. The silica nanoparticles of low hydrophobicity tend to form a contact angle greater than 90 degrees at the oil-water interface thereby improving water wetting of particle surface resulting in an unstable water-in-oil emulsion [31, 32].

The hydrophobic nature of silica nanoparticles also affects the inversion point. As observed in Figures 5.5 and 5.6, the more hydrophobic silica (HDK H20) increases the dispersed phase volume fraction where phase inversion occurs as compared with less hydrophobic HDK HKS D.

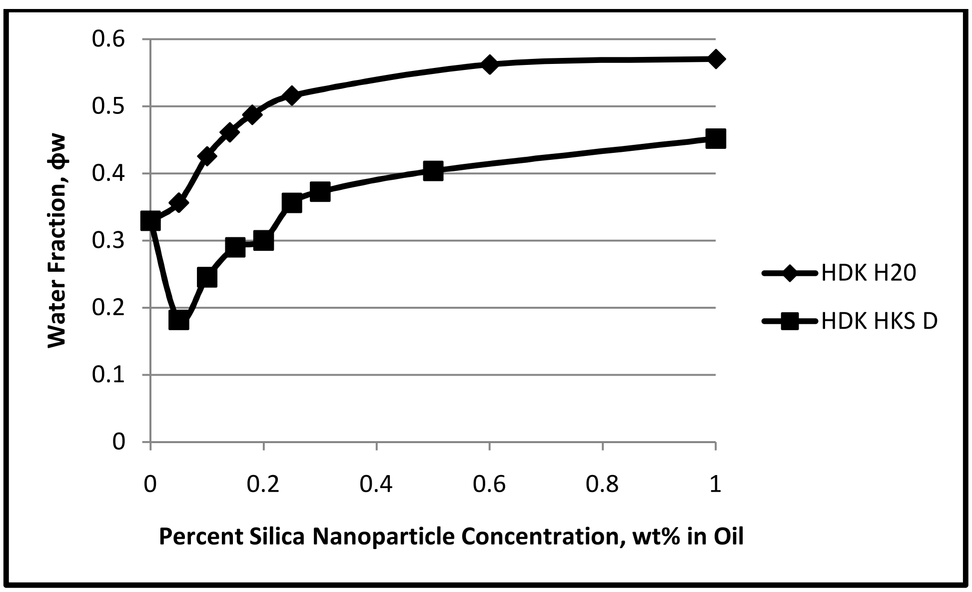


Figure 5.5 Comparison trends showing the effect of hydrophobicity of silica nanoparticles on the phase inversion points (Oil A)

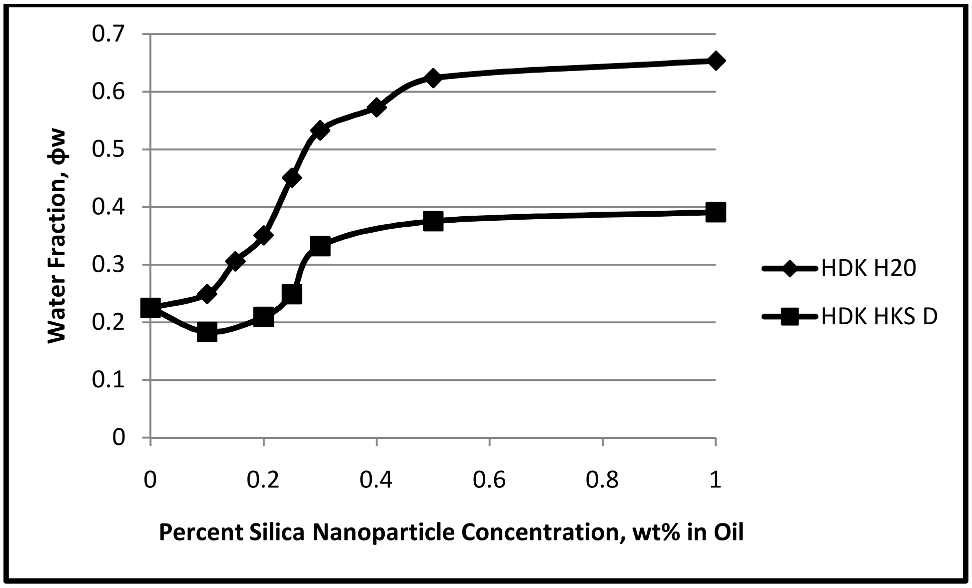


Figure 5.6 Comparison trends showing the effect of hydrophobicity of silica nanoparticles on the phase inversion points (Oil B)

This once again is due to the wetting property of silica nanoparticles at the oil-water interface. More hydrophobic HDK H20 forms a contact angle less than 90 degrees whereas HKS D tends to form a contact angle greater than 90 degrees resulting in unstable water-in-oil emulsions.

5.3. Effect of Oil Viscosity on stability and phase inversion

As discussed earlier in the results, experiments were conducted with two different viscosity oils (Oil A - 22.9mPa.s and Oil B – 64.5mPa.s). The volume fraction of water at phase inversion was significantly lower for the higher viscosity oil. The effect of viscosity has been explained earlier by Paul and Barlow [33] for phase inversion of different immiscible polymer blends. According to their explanation, the water volume fraction at which phase inversion occurs is given by:

$$\phi_W = \frac{1}{1+\lambda} \qquad (1)$$

where, $\lambda = \frac{\eta_o}{\eta_w}$, η_o = viscosity of oil, and η_w = viscosity of water

Consequently, as the viscosity of oil is raised the denominator increases due to an increase in the value of λ. Therefore, from equation 1 above, it is determined that with an increase in the denominator caused by an increase in the oil viscosity, the volume fraction at which phase inversion occurs goes down. This is further confirmed by Utracki [33], who proposed:

$$\phi_W = \frac{1-0.5263 log\lambda}{2} \qquad (2)$$

Once again, the λ value increases with increasing oil viscosity. This causes a reduction in the numerator which implies that the phase inversion point also reduces. These calculations produce similar trends to the ones observed in the experimental data.

The stability of water-in-oil emulsions prepared from the two oils of different viscosities was also studied. Figure 5.7 clearly show that the rate of separation of water slows down considerably with the increase in the viscosity of oil.

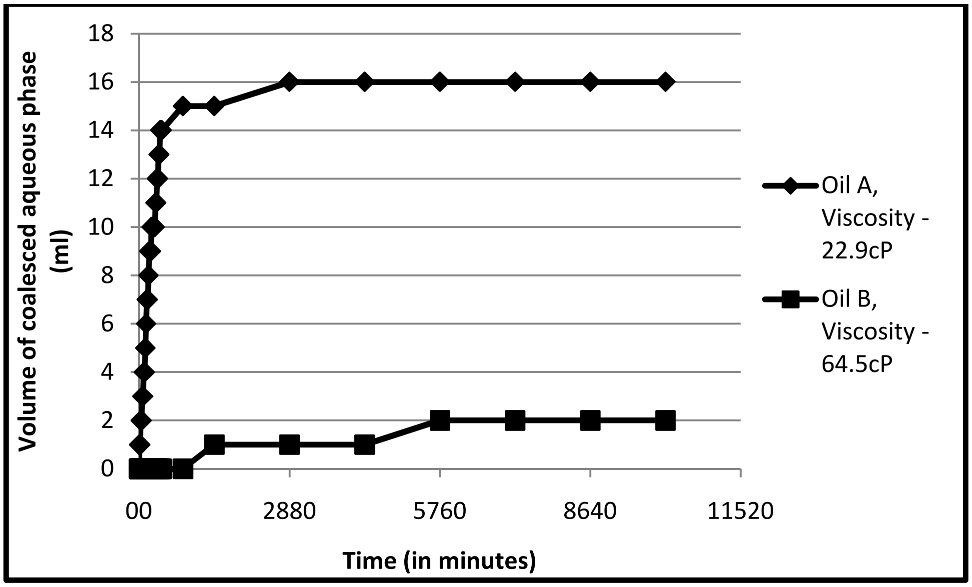


Figure 5.7 The effect of oil viscosity on coalescence behaviour of emulsions stabilized with surfactant alone

By using higher viscosity oil, the rate of coalescence of water-in-oil emulsion is reduced as gravitational settling of the water droplets slows down considerably. Furthermore, the thinning of oil film between the water droplets, and hence coalescence, takes a longer time when the oil viscosity is increased.

Chapter 6. CONCLUSIONS

The phenomenon of phase inversion from W/O (water-in-oil) emulsion to O/W (oil-in-water) emulsion was studied using surfactant, solid nanoparticles, and mixed surfactant-nanoparticles as stabilizers. The effect of oil viscosity on phase inversion was also investigated. Finally, the stability of emulsions was investigated using individual and mixed stabilizers. Based on the experimental results, the following conclusions can be made:

- Surfactant is much more effective in delaying the phase inversion of W/O emulsion to O/W emulsion as compared with the nanoparticles, when comparison is made at the same stabilizer concentration. For the same concentration of 0.1 wt% stabilizer initially dispersed in oil, surfactant stabilized W/O emulsion inverted to O/W emulsion at 72% by volume water whereas silica nanoparticle stabilized emulsion inverted at 31% by volume water. This is probably due to the greater affinity of surfactant for the oil-water interface.

- For emulsions stabilized with silica nanoparticles, the higher hydrophobic grade particles are more effective in delaying the phase inversion of W/O emulsion to O/W emulsion. At 0.1 wt% concentration of silica nanoparticles (based on oil phase) HKS D (30% hydrophobic) gives a phase inversion value of 18 percent by volume compared to 32% given by H20 (50% hydrophobic), the higher hydrophobic grade. This can be explained in terms of the wetting ability of the solid nanoparticle at the oil-water interface.

- With increasing proportion of surfactant in the mixed surfactant/nanoparticles stabilizer, the water fraction at which phase inversion occurs increases. This proves that the surfactant plays a more dominant role in determining the phase inversion point.

- With increasing proportion of silica nanoparticles in the mixed surfactant/nanoparticle stabilizer, the emulsion formed is much more stable as compared to emulsion formed using a lower nanoparticle to surfactant ratio. Surfactant alone gives an unstable W/O emulsion and leads to quick separation of the aqueous phase.

- By increasing the viscosity of oil, the dispersed volume fraction of the aqueous phase at which phase inversion occurs is reduced significantly. However, increasing the oil viscosity improves the emulsion stability significantly with respect to coalescence.

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APPENDICES

Appendix A: Raw Data

Appendix A-1: Experimental Data Points for Oil A, Viscosity: 22.9mPa.s

***No Stabilizer Added*, Oil-Water Emulsion System**

Surfactant-Solids Concentration		0.0 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
217	0.310	0.01
227	0.320	0.64
237	**0.329**	**174.7**
257	**0.347**	**225.4**
267	**0.356**	**268**
287	**0.373**	**282.6**
327	**0.404**	**312**
353	**0.425**	**344**
393	**0.452**	**368**
423	**0.470**	**387**
483	**0.503**	**401**
523	**0.523**	**431**
593	**0.554**	**484**
633	**0.570**	**497**
723	**0.603**	**531**
793	**0.624**	**561**
893	**0.652**	**587**
973	**0.671**	**604**
1133	**0.704**	**669**
1233	**0.721**	**684**
1433	**0.750**	**737**

EMSORB 2503 – Surfactant Only

Surfactant Concentration		0.1 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
10	0.038	0.01
20	0.074	0.01
30	0.107	0.01
40	0.138	0.01
50	0.167	0.01
60	0.194	0.01
70	0.219	0.01
80	0.242	0.01
90	0.265	0.01
100	0.286	0.01
110	0.306	0.01
120	0.324	0.01
130	0.342	0.01
140	0.359	0.01
150	0.375	0.01
160	0.390	0.01
170	0.405	0.01
180	0.419	0.01
190	0.432	0.01
200	0.444	0.01
210	0.457	0.34
220	0.468	1.16
230	0.479	1.97
240	0.490	2.23
250	0.500	2.26
270	0.519	2.57
290	0.537	2.97
310	0.554	3.79
330	0.569	4.5
350	0.583	4.74
380	0.603	5.4
420	0.627	5.52
470	0.653	5.8
530	0.679	8.82
590	0.702	9.34
650	**0.722**	**624**
750	**0.750**	**688**
870	**0.777**	**757**
1000	**0.800**	**800**
1250	**0.833**	**860**
1370	**0.846**	**888**

Surfactant Concentration		0.05 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
10	0.032	0.01
20	0.063	0.01
35	0.104	0.01
44	0.131	0.01
54	0.157	0.01
64	0.180	0.01
74	0.203	0.01
82	0.225	0.01
92	0.245	0.01
102	0.265	0.01
112	0.284	0.01
122	0.301	0.01
132	0.318	0.01
142	0.334	0.01
152	0.349	0.01
162	0.364	0.01
172	0.378	0.01
182	0.391	1.36
192	0.404	1.5
198	0.417	1.69
208	0.429	1.71
218	0.440	1.72
228	0.451	2.17
238	0.462	2.41
248	0.472	2.48
268	0.492	2.49
288	0.510	2.84
308	0.526	4.5
328	0.542	7.33
348	0.557	7.96
378	0.577	9.65
418	0.601	11.77
448	0.618	13.76
508	0.647	9.76
548	0.664	12.88
648	**0.701**	**445**
678	**0.710**	**503**
718	**0.722**	**533**
808	**0.745**	**581**
928	**0.770**	**640**
988	**0.781**	**669**

Surfactant Concentration		0.03 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
10	0.032	0.01
20	0.063	0.01
35	0.104	0.01
44	0.131	0.01
54	0.157	0.01
64	0.180	0.01
74	0.203	0.01
82	0.225	0.01
92	0.245	0.01
102	0.265	0.01
112	0.284	0.05
122	0.301	0.09
132	0.318	0.42
142	0.334	1.94
152	0.349	1.5
162	0.364	2.28
172	0.378	1.86
182	0.391	1.25
192	0.404	1.22
198	0.417	2.01
208	0.429	2.85
218	0.440	3.03
228	0.451	3.45
238	0.462	4.5
248	0.472	6.2
268	0.492	2.54
288	0.510	2.17
308	0.526	10.17
328	0.542	12.54
348	0.557	14.86
378	0.577	16.05
418	0.601	21.86
458	**0.623**	**370**
508	**0.647**	**424**
568	**0.672**	**471**
648	**0.701**	**528**
718	**0.722**	**567**
848	**0.754**	**634**
938	**0.772**	**663**

Surfactant Concentration		0.02 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.04
89	0.153	0.05
109	0.182	0.09
129	0.208	0.1
137	0.221	0.11
157	0.245	0.13
187	0.279	0.2
207	0.300	0.22
237	0.329	0.23
267	0.356	0.28
287	0.373	0.3
307	0.389	0.3
327	0.404	0.31
363	0.432	0.32
383	0.445	0.5
393	0.452	0.52
423	0.470	0.55
443	0.482	0.86
463	0.493	0.92
483	0.503	1.22
503	0.513	1.47
523	0.523	1.53
543	0.532	1.68
573	0.546	1.82
593	0.554	1.89
613	0.562	3.92
633	0.570	4.65
663	**0.582**	**326**
693	**0.592**	**362**
723	**0.603**	**393**
783	**0.621**	**448**
893	**0.652**	**537**
973	**0.671**	**582**
1133	**0.704**	**617**
1233	**0.721**	**651**
1393	**0.745**	**686**

Surfactant Concentration		0.01 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
10	0.032	0.01
20	0.063	0.01
35	0.104	0.01
44	0.131	0.01
54	0.157	0.01
64	0.180	0.01
74	0.203	0.01
82	0.225	0.01
92	0.245	0.01
102	0.265	0.01
112	0.284	0.01
122	0.301	0.01
132	0.318	0.01
152	0.349	0.01
162	0.364	0.01
172	0.378	0.01
182	0.391	0.02
192	0.404	0.02
208	0.429	0.01
228	0.451	0.03
238	0.462	0.08
248	0.472	0.11
258	0.482	0.14
268	0.492	0.16
288	0.510	0.28
298	0.518	0.34
308	0.526	0.51
318	**0.534**	**297.1**
328	**0.542**	**353**
348	**0.557**	**397**
373	**0.574**	**415**
418	**0.601**	**467**
458	**0.623**	**495**
518	**0.652**	**531**
568	**0.672**	**575**
648	**0.701**	**630**
718	**0.722**	**642**
848	**0.754**	**701**
948	**0.774**	**756**

Surfactant Concentration		0.007 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
10	0.032	0.01
20	0.063	0.01
35	0.104	0.01
44	0.131	0.01
54	0.157	0.01
64	0.180	0.01
74	0.203	0.01
82	0.225	0.01
92	0.245	0.02
102	0.265	0.04
112	0.284	0.05
122	0.301	0.11
132	0.318	0.19
152	0.349	0.27
162	0.364	0.31
172	0.378	0.35
182	0.391	0.41
192	0.404	0.45
208	0.429	0.5
228	0.451	0.71
238	0.462	0.73
248	0.472	0.82
258	0.482	0.83
268	0.492	1.04
278	0.501	1.21
293	0.514	1.45
308	0.526	2.08
318	**0.534**	**399**
328	**0.542**	**437**
348	**0.557**	**446**
373	**0.574**	**485**
418	**0.601**	**495**
458	**0.623**	**542**
518	**0.652**	**576**
568	**0.672**	**611**
648	**0.701**	**644**
718	**0.722**	**683**
848	**0.754**	**732**
948	**0.774**	**774**

Surfactant Concentration		0.004 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.032	0.01
40	0.063	0.01
70	0.104	0.01
89	0.131	0.01
109	0.156	0.01
129	0.179	0.01
149	0.201	0.01
167	0.223	0.01
187	0.243	0.01
207	0.262	0.02
227	0.280	0.05
247	0.298	0.06
267	0.314	0.1
287	0.330	0.09
307	0.345	0.07
327	0.359	0.1
347	0.373	0.1
367	0.386	0.15
387	0.399	0.23
397	0.405	0.29
413	0.417	0.28
433	0.429	0.35
453	**0.440**	**254.1**
473	**0.450**	**296**
493	**0.461**	**311**
513	**0.471**	**346**
583	**0.503**	**377**
633	**0.523**	**395**
713	**0.553**	**417**
783	**0.576**	**461**
868	**0.601**	**496**
948	**0.622**	**513**
1078	**0.651**	**551**
1178	**0.671**	**561**
1348	**0.700**	**577**
1508	**0.723**	**669**
1608	**0.736**	**725**

HDK H20 (50% hydrophobic) – Silica Nanoparticle Only

Silica (H20) Concentration		1.0 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
167	0.257	0.01
187	0.279	0.01
207	0.300	0.01
217	0.310	0.04
237	0.329	0.07
267	0.356	0.15
287	0.373	0.09
327	0.404	0.08
353	0.425	0.15
373	0.439	0.15
393	0.452	0.16
423	0.470	0.19
483	0.503	0.39
503	0.513	0.32
513	0.518	0.43
543	0.532	0.62
593	0.554	1.36
613	0.562	1.62
633	**0.570**	**346**
663	**0.582**	**425**
693	**0.592**	**464**
713	**0.599**	**489**
783	**0.621**	**520**
893	**0.652**	**568**
973	**0.671**	**597**
1133	**0.704**	**645**
1233	**0.721**	**669**
1393	**0.745**	**703**

Silica Concentration (H20)		0.6 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
167	0.257	0.01
187	0.279	0.01
207	0.300	0.01
237	0.329	0.04
257	0.347	0.01
267	0.356	0.01
287	0.373	0.03
307	0.389	0.02
327	0.404	0.04
347	0.421	0.1
382	0.445	0.34
392	0.451	0.37
427	0.472	0.45
462	0.492	0.64
482	0.503	0.83
512	0.518	0.94
552	0.536	1.17
572	0.545	1.42
592	0.554	2.87
612	**0.562**	**290.7**
637	**0.572**	**337**
717	**0.601**	**397**
782	**0.621**	**454**
892	**0.652**	**493**
972	**0.671**	**520**
1132	**0.704**	**567**
1232	**0.721**	**590**
1402	**0.746**	**627**

Silica Concentration (H20)		0.25 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.02
177	0.268	0.05
187	0.279	0.26
207	0.300	0.4
217	0.310	0.68
237	0.329	0.67
257	0.347	0.7
267	0.356	0.73
287	0.373	1
327	0.404	1.32
343	0.418	1.37
363	0.432	1.28
373	0.439	1.3
393	0.452	1.68
423	0.470	2.4
443	0.482	4.3
463	0.493	4.37
483	0.503	5.31
488	0.506	5.8
508	**0.516**	**380**
543	**0.532**	**418**
573	**0.546**	**443**
593	**0.554**	**455**
633	**0.570**	**479**
713	**0.599**	**516**
783	**0.621**	**545**
893	**0.652**	**586**
973	**0.671**	**611**
1133	**0.704**	**659**
1233	**0.721**	**686**
1433	**0.750**	**729**

Silica Concentration (H20)		0.18 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
187	0.279	0.01
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
257	0.347	0.01
267	0.356	0.73
287	0.373	0.63
297	0.381	2.34
317	0.396	1.51
327	0.404	4.45
343	0.418	7.27
363	0.432	8.23
373	0.439	7.62
393	0.452	4.62
403	0.458	6.59
423	0.470	8.45
443	**0.482**	**345**
463	**0.493**	**382**
488	**0.506**	**406**
513	**0.518**	**434**
593	**0.554**	**475**
633	**0.570**	**496**
713	**0.599**	**533**
783	**0.621**	**561**
893	**0.652**	**598**
973	**0.671**	**622**
1133	**0.704**	**668**
1233	**0.721**	**692**
1403	**0.746**	**729**

Silica Concentration (H20)		0.16 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.04
79	0.139	0.17
89	0.153	3.74
109	0.182	3.96
129	0.208	4.7
137	0.221	5.16
157	0.245	5.34
167	0.257	5.49
187	0.279	5.54
207	0.300	5.64
217	0.310	5.89
237	0.329	6.16
247	0.338	6.2
257	0.347	6.49
267	0.356	6.51
277	0.364	6.63
287	0.373	6.85
297	0.381	7.15
317	0.396	7.2
327	0.404	7.37
333	0.411	7.57
353	0.425	7.76
368	0.436	8.26
378	0.442	8.57
393	0.452	9.16
408	0.461	10.1
423	0.470	10.76
453	**0.487**	**276.9**
483	**0.503**	**313**
518	**0.521**	**334**
593	**0.554**	**373**
723	**0.603**	**432**
893	**0.652**	**491**
1113	**0.700**	**556**
1263	**0.726**	**589**
1353	**0.739**	**622**

Silica Concentration (H20)		0.14 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.09
89	0.153	0.09
109	0.182	0.09
129	0.208	0.1
137	0.221	0.12
157	0.245	0.13
167	0.257	0.13
187	0.279	0.13
207	0.300	0.13
237	0.329	1.53
247	0.338	1.63
267	0.356	1.81
277	0.364	1.99
287	0.373	2.47
297	0.381	2.72
317	0.396	2.83
327	0.404	3.03
333	0.411	3.06
353	0.425	3.27
368	0.436	3.41
378	0.442	3.54
393	0.452	3.64
408	**0.461**	**275.5**
423	**0.470**	**303**
453	**0.487**	**356**
483	**0.503**	**393**
523	**0.523**	**432**
593	**0.554**	**469**
633	**0.570**	**490**
723	**0.603**	**525**
793	**0.624**	**530**
893	**0.652**	**583**
973	**0.671**	**611**
1113	**0.700**	**630**
1263	**0.726**	**671**
1413	**0.748**	**706**

Silica Concentration (H20)		0.1 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
167	0.257	0.12
187	0.279	0.12
207	0.300	0.13
237	0.329	0.41
257	0.347	1.28
267	0.356	1.58
277	0.364	1.64
287	0.373	1.72
297	0.381	1.82
317	0.396	1.82
327	**0.404**	**202.1**
333	**0.411**	**224.1**
353	**0.425**	**248.6**
368	**0.436**	**291.7**
378	**0.442**	**308**
393	**0.452**	**319**
423	**0.470**	**335**
483	**0.503**	**365**
523	**0.523**	**401**
593	**0.554**	**437**
633	**0.570**	**443**
723	**0.603**	**472**
793	**0.624**	**492**
893	**0.652**	**542**
973	**0.671**	**590**
1113	**0.700**	**630**
1263	**0.726**	**669**
1433	**0.750**	**703**

Silica Concentration (H20)		0.05 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
167	0.257	0.01
187	0.279	0.01
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
247	0.338	0.51
257	0.347	7.32
267	**0.356**	**195.8**
277	**0.364**	**221.4**
287	**0.373**	**248.5**
327	**0.404**	**280.2**
357	**0.425**	**297.5**
397	**0.451**	**367**
427	**0.469**	**399**
487	**0.502**	**414**
517	**0.517**	**429**
597	**0.553**	**467**
637	**0.569**	**490**
717	**0.598**	**519**
787	**0.620**	**548**
887	**0.647**	**589**
987	**0.671**	**618**
1117	**0.698**	**660**
1267	**0.724**	**693**
1447	**0.750**	**727**

HDK HKS D (30% hydrophobic) – Silica Nanoparticle Only

Silica Concentration (HKS D)		3 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.03
267	0.356	0.04
287	0.373	0.06
307	0.389	0.14
327	0.404	0.14
353	0.425	0.16
393	0.452	0.23
413	0.464	0.24
423	0.470	0.28
443	0.482	0.35
483	0.503	0.43
503	0.513	0.55
523	0.523	1.08
553	**0.537**	**356**
573	**0.546**	**408**
593	**0.554**	**423**
633	**0.570**	**454**
723	**0.603**	**494**
793	**0.624**	**537**
893	**0.652**	**564**
973	**0.671**	**583**
1133	**0.704**	**645**
1233	**0.721**	**663**
1423	**0.749**	**710**

Silica Concentration (HKS D)		2 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.02
287	0.373	0.06
307	0.389	0.06
327	0.404	0.07
353	0.425	0.08
373	0.439	0.09
383	0.445	0.11
393	0.452	0.21
413	0.464	0.24
423	0.470	0.31
443	0.482	1.72
463	0.493	2.21
483	**0.503**	**348**
523	**0.523**	**373**
593	**0.554**	**423**
633	**0.570**	**443**
723	**0.603**	**489**
793	**0.624**	**529**
893	**0.652**	**564**
973	**0.671**	**589**
1133	**0.704**	**640**
1233	**0.721**	**667**
1433	**0.750**	**711**

Silica Concentration (HKS D)		1 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
257	0.347	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
343	0.418	0.01
353	0.425	0.18
373	0.439	0.19
393	**0.452**	**296**
423	**0.470**	**328**
443	**0.482**	**351**
463	**0.493**	**369**
483	**0.503**	**386**
523	**0.523**	**404**
593	**0.554**	**448**
633	**0.570**	**472**
723	**0.603**	**515**
793	**0.624**	**533**
893	**0.652**	**576**
973	**0.671**	**597**
1133	**0.704**	**662**
1233	**0.721**	**689**
1343	**0.738**	**712**

Silica Concentration (HKS D)		0.5 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.02
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.02
177	0.268	0.01
197	0.290	0.04
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
257	0.347	0.01
267	0.356	0.01
287	0.373	1.31
307	0.389	3.28
327	**0.404**	**314**
343	**0.418**	**328**
353	**0.425**	**333**
393	**0.452**	**357**
423	**0.470**	**375**
483	**0.503**	**422**
523	**0.523**	**442**
593	**0.554**	**481**
633	**0.570**	**500**
723	**0.603**	**526**
793	**0.624**	**575**
893	**0.652**	**608**
973	**0.671**	**629**
1133	**0.704**	**650**
1233	**0.721**	**707**
1433	**0.750**	**750**

Silica Concentration (HKS D)		0.3 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.02
129	0.208	0.03
137	0.221	0.03
157	0.245	0.04
177	0.268	0.07
197	0.290	0.07
207	0.300	0.09
217	0.310	0.13
237	0.329	0.15
257	0.347	0.26
267	0.356	0.84
287	**0.373**	**262.4**
307	**0.389**	**287.3**
327	**0.404**	**324**
353	**0.425**	**348**
393	**0.452**	**368**
423	**0.470**	**393**
483	**0.503**	**425**
523	**0.523**	**446**
593	**0.554**	**477**
633	**0.570**	**500**
723	**0.603**	**533**
793	**0.624**	**562**
893	**0.652**	**596**
973	**0.671**	**622**
1133	**0.704**	**664**
1233	**0.721**	**688**
1423	**0.749**	**728**

Silica Concentration (HKS D)		0.25 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.03
207	0.300	0.04
217	0.310	0.04
237	0.329	0.05
257	0.347	0.09
267	**0.356**	**195.4**
287	**0.373**	**257.6**
307	**0.389**	**296**
327	**0.404**	**296.3**
353	**0.425**	**336**
393	**0.452**	**352**
423	**0.470**	**370**
483	**0.503**	**401**
523	**0.523**	**425**
593	**0.554**	**471**
633	**0.570**	**481**
723	**0.603**	**516**
793	**0.624**	**544**
893	**0.652**	**572**
973	**0.671**	**604**
1133	**0.704**	**652**
1233	**0.721**	**678**
1443	**0.752**	**729**

Silica Concentration (HKS D)		0.2 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.06
157	0.245	0.14
177	0.268	0.15
197	0.290	0.18
207	**0.300**	**197.1**
217	**0.310**	**214.3**
237	**0.329**	**229.6**
267	**0.356**	**272.8**
287	**0.373**	**293.7**
327	**0.404**	**312**
353	**0.425**	**334**
393	**0.452**	**360**
423	**0.470**	**382**
483	**0.503**	**412**
523	**0.523**	**437**
593	**0.554**	**470**
633	**0.570**	**492**
723	**0.603**	**531**
793	**0.624**	**558**
893	**0.652**	**590**
973	**0.671**	**622**
1133	**0.704**	**668**
1233	**0.721**	**684**
1443	**0.752**	**728**

Silica Concentration (HKS D)		0.15 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.03
109	0.182	0.06
129	0.208	0.07
137	0.221	0.08
157	0.245	0.17
167	0.257	0.24
177	0.268	0.56
187	0.279	2.56
197	**0.290**	**155.6**
207	**0.300**	**176.2**
237	**0.329**	**208**
267	**0.356**	**235.2**
287	**0.373**	**256**
327	**0.404**	**287.5**
353	**0.425**	**301**
393	**0.452**	**342**
423	**0.470**	**357**
483	**0.503**	**398**
523	**0.523**	**414**
593	**0.554**	**443**
633	**0.570**	**465**
723	**0.603**	**508**
793	**0.624**	**537**
893	**0.652**	**572**
973	**0.671**	**602**
1133	**0.704**	**656**
1233	**0.721**	**678**
1483	**0.757**	**734**

Silica Concentration (HKS D)		0.1 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.03
79	0.139	0.04
89	0.153	0.05
109	0.182	0.06
129	0.208	0.06
137	0.221	0.09
157	**0.245**	**144.7**
177	**0.268**	**151.2**
197	**0.290**	**171.4**
207	**0.300**	**181.5**
237	**0.329**	**182.2**
267	**0.356**	**236.7**
287	**0.373**	**250**
327	**0.404**	**295.8**
353	**0.425**	**303**
393	**0.452**	**353**
423	**0.470**	**380**
483	**0.503**	**405**
523	**0.523**	**438**
593	**0.554**	**472**
633	**0.570**	**491**
723	**0.603**	**532**
793	**0.624**	**561**
893	**0.652**	**598**
973	**0.671**	**638**
1133	**0.704**	**678**
1233	**0.721**	**690**
1473	**0.755**	**744**

Silica Concentration (HKS D)		0.05 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
99	0.168	0.04
109	**0.182**	**94.3**
129	**0.208**	**121.2**
137	**0.221**	**124.3**
167	**0.257**	**152.3**
187	**0.279**	**170.2**
207	**0.300**	**189.6**
237	**0.329**	**236.4**
267	**0.356**	**256.3**
287	**0.373**	**271.1**
327	**0.404**	**307**
353	**0.425**	**331**
393	**0.452**	**356**
423	**0.470**	**387**
483	**0.503**	**428**
523	**0.523**	**471**
593	**0.554**	**487**
633	**0.570**	**527**
723	**0.603**	**571**
793	**0.624**	**587**
893	**0.652**	**615**
973	**0.671**	**656**
1133	**0.704**	**690**
1233	**0.721**	**718**
1433	**0.750**	**751**

Combination – HDK H20 (50 Silica Nanoparticle) + EMSORB 2503 (Surfactant)

Surfactant - EMSORB 2503		0.003 wt%
Silica Concentration (H20)		0.095 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
187	0.279	0.01
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	1.78
297	0.381	3.37
317	0.396	6.28
327	0.404	6.47
333	**0.411**	**214.28**
353	**0.425**	**265.9**
373	**0.439**	**322**
393	**0.452**	**367**
433	**0.476**	**384**
483	**0.503**	**417**
523	**0.523**	**448**
593	**0.554**	**462**
643	**0.574**	**471**
723	**0.603**	**512**
793	**0.624**	**552**
893	**0.652**	**585**
983	**0.673**	**603**
1133	**0.704**	**617**
1233	**0.721**	**642**
1433	**0.750**	**686**

Surfactant - EMSORB 2503		0.007 wt%
Silica Concentration (H20)		0.093 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
310	0.383	0.01
340	0.405	0.01
350	0.412	0.01
370	0.425	0.01
390	0.438	0.01
400	**0.444**	**301**
410	**0.451**	**358**
450	**0.474**	**365**
510	**0.505**	**419**
550	**0.524**	**425**
620	**0.554**	**451**
670	**0.573**	**471**
760	**0.603**	**503**
820	**0.621**	**541**
930	**0.650**	**575**
1030	**0.673**	**607**
1190	**0.704**	**634**
1290	**0.721**	**667**
1480	**0.747**	**715**

Surfactant - EMSORB 2503		0.01 wt%
Silica Concentration (H20)		0.09 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
187	0.279	0.01
207	0.300	0.01
217	0.310	0.01
237	0.329	0.01
257	0.347	0.01
277	0.364	0.01
287	0.373	0.01
297	0.381	0.01
317	0.396	0.02
327	0.404	0.04
343	0.418	0.04
363	0.432	0.14
393	0.452	0.19
423	0.470	0.21
443	0.482	0.25
463	0.493	3.21
483	**0.503**	**298**
493	**0.508**	**346**
513	**0.518**	**361**
583	**0.550**	**388**
633	**0.570**	**424**
713	**0.599**	**463**
783	**0.621**	**495**
893	**0.652**	**549**
973	**0.671**	**574**
1133	**0.704**	**616**
1233	**0.721**	**654**
1413	**0.748**	**705**

Surfactant - EMSORB 2503		0.02 wt%
Silica Concentration (H20)		0.08 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.02
187	0.279	0.02
207	0.300	0.03
237	0.329	0.03
257	0.347	0.03
267	0.356	0.04
287	0.373	0.04
297	0.381	0.04
327	0.404	0.04
343	0.418	0.04
363	0.432	0.04
373	0.439	0.04
393	0.452	0.07
423	0.470	0.16
463	0.493	0.78
483	0.503	1.84
513	0.518	2.24
543	**0.532**	**299.5**
563	**0.541**	**346**
583	**0.550**	**374**
613	**0.562**	**414**
633	**0.570**	**424**
713	**0.599**	**464**
783	**0.621**	**488**
893	**0.652**	**537**
973	**0.671**	**573**
1133	**0.704**	**603**
1233	**0.721**	**653**
1403	**0.746**	**688**

Surfactant - EMSORB 2503		0.03 wt%
Silica Concentration (H20)		0.07 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
207	0.300	0.01
237	0.329	0.01
257	0.347	0.02
267	0.356	0.02
287	0.373	0.03
297	0.381	0.03
327	0.404	0.03
363	0.432	0.05
403	0.458	0.06
423	0.470	0.06
443	0.482	0.05
463	0.493	0.11
483	0.503	0.16
513	0.518	0.23
543	0.532	0.32
563	0.541	0.54
583	0.550	1.55
613	0.562	1.66
633	**0.570**	**313**
663	**0.582**	**391**
693	**0.592**	**434**
713	**0.599**	**455**
783	**0.621**	**504**
893	**0.652**	**547**
973	**0.671**	**581**
1133	**0.704**	**625**
1233	**0.721**	**655**
1393	**0.745**	**705**

Surfactant - EMSORB 2503		0.04 wt%
Silica Concentration (H20)		0.06 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
207	0.300	0.01
237	0.329	0.01
257	0.347	0.01
267	0.356	0.01
287	0.373	0.01
297	0.381	0.01
327	0.404	0.01
343	0.418	0.01
363	0.432	0.01
403	0.458	0.01
423	0.470	0.01
443	0.482	0.01
483	0.503	0.01
523	0.523	0.01
563	0.541	0.01
583	0.550	0.03
613	0.562	0.04
633	0.570	0.06
663	0.582	0.07
693	0.592	0.15
718	**0.601**	**351**
743	**0.611**	**442**
782	**0.623**	**487**
893	**0.654**	**509**
973	**0.673**	**529**
1133	**0.705**	**578**
1233	**0.723**	**624**
1343	**0.740**	**654**

Surfactant - EMSORB 2503		0.05 wt%
Silica Concentration (H20)		**0.05 wt%**
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
187	0.279	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
327	0.404	0.01
353	0.425	0.01
393	0.452	0.01
423	0.470	0.01
483	0.503	0.01
523	0.523	0.01
583	0.550	0.01
613	0.562	0.01
633	0.570	0.01
663	0.582	0.01
693	0.592	0.01
718	0.601	0.27
743	0.611	1.5
783	0.623	2.79
813	**0.632**	**503**
853	**0.643**	**526**
893	**0.654**	**567**
973	**0.673**	**601**
1133	**0.705**	**634**
1233	**0.723**	**654**
1313	**0.735**	**691**

Surfactant - EMSORB 2503		0.07 wt%
Silica Concentration (H20)		**0.03 wt%**
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
670	0.573	0.01
760	0.603	0.01
820	0.621	0.01
930	0.650	0.01
1030	0.673	0.01
1070	0.682	0.01
1120	0.691	0.01
1190	**0.704**	**451**
1240	**0.713**	**488**
1290	**0.721**	**584**
1430	**0.741**	**674**

Combination – HDK HKS D (30% Silica Nanoparticle) + EMSORB 2503 (Surfactant)

Surfactant - EMSORB 2503		0.005 wt%
Silica Concentration (HKS D)		0.095 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
260	0.342	0.01
270	**0.351**	**161.3**
290	**0.367**	**182.1**
300	**0.375**	**202.5**
340	**0.405**	**232.6**
370	**0.425**	**254.9**
390	**0.438**	**272.4**
400	**0.444**	**301**
410	**0.451**	**358**
450	**0.474**	**365**
510	**0.505**	**419**
550	**0.524**	**425**
620	**0.554**	**451**
670	**0.573**	**471**
760	**0.603**	**503**
820	**0.621**	**541**
930	**0.650**	**575**
1030	**0.673**	**607**
1190	**0.704**	**634**
1290	**0.721**	**667**
1480	**0.747**	**715**

Surfactant - EMSORB 2503		0.01 wt%
Silica Concentration (HKS D)		0.09 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
167	0.257	0.01
177	0.268	0.02
187	0.279	0.03
207	0.300	0.05
237	0.329	0.1
267	0.356	0.29
287	0.373	0.71
297	0.381	0.84
327	0.404	1.94
343	0.418	2.16
353	0.425	2.87
363	0.432	3.16
383	0.445	3.56
393	**0.452**	**290.4**
403	**0.458**	**331**
423	**0.470**	**361**
483	**0.503**	**398**
523	**0.523**	**423**
583	**0.550**	**458**
633	**0.570**	**480**
723	**0.603**	**519**
783	**0.621**	**542**
893	**0.652**	**579**
973	**0.671**	**607**
1133	**0.704**	**649**
1233	**0.721**	**670**
1423	**0.749**	**707**

Surfactant - EMSORB 2503		0.02 wt%
Silica Concentration (HKS D)		0.08 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
167	0.257	0.01
177	0.268	0.01
187	0.279	0.01
197	0.290	0.01
207	0.300	0.02
237	0.329	0.03
267	0.356	0.04
287	0.373	0.05
327	0.404	0.08
343	0.418	0.1
353	0.425	0.11
393	0.452	0.2
413	0.464	0.24
423	0.470	0.28
443	0.482	0.3
483	0.503	0.47
503	0.513	0.63
523	0.523	0.71
553	**0.537**	**328**
563	**0.541**	**357**
583	**0.550**	**372**
633	**0.570**	**403**
723	**0.603**	**458**
783	**0.621**	**484**
893	**0.652**	**528**
973	**0.671**	**558**
1133	**0.704**	**604**
1233	**0.721**	**636**
1443	**0.752**	**684**

Surfactant - EMSORB 2503		0.03 wt%
Silica Concentration (HKS D)		0.07 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.03
307	0.389	0.03
327	0.404	0.04
343	0.418	0.05
363	0.432	0.06
393	0.452	0.08
413	0.464	0.11
443	0.482	0.13
463	0.493	0.14
483	0.503	0.15
503	0.513	0.21
523	0.523	0.25
543	0.532	0.26
563	0.541	0.34
583	0.550	1.57
613	**0.562**	**384**
633	**0.570**	**402**
723	**0.603**	**443**
783	**0.621**	**473**
893	**0.652**	**517**
973	**0.671**	**545**
1133	**0.704**	**592**
1233	**0.721**	**623**
1443	**0.752**	**668**

Surfactant - EMSORB 2503		0.04 wt%
Silica Concentration (HKS D)		0.06 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.02
307	0.389	0.03
327	0.404	0.04
363	0.432	0.06
383	0.445	0.06
403	0.458	0.07
433	0.476	0.08
483	0.503	0.13
503	0.513	0.15
523	0.523	0.17
543	0.532	0.18
563	0.541	0.22
583	0.550	0.43
613	0.562	0.51
633	0.570	0.83
663	**0.582**	**355**
693	**0.592**	**403**
723	**0.603**	**428**
783	**0.621**	**467**
893	**0.652**	**507**
973	**0.671**	**540**
1133	**0.704**	**606**
1233	**0.721**	**634**
1403	**0.746**	**661**

Surfactant - EMSORB 2503		0.05 wt%
Silica Concentration (HKS D)		0.05 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
363	0.432	0.01
383	0.445	0.01
403	0.458	0.01
433	0.476	0.02
483	0.503	0.05
503	0.513	0.08
523	0.523	0.09
543	0.532	0.11
563	0.541	0.14
583	0.550	0.17
613	0.562	0.21
643	0.574	0.24
663	0.582	0.3
693	0.592	0.36
723	**0.603**	**399**
783	**0.621**	**443**
893	**0.652**	**495**
973	**0.671**	**529**
1133	**0.704**	**585**
1233	**0.721**	**617**
1413	**0.748**	**655**

Surfactant - EMSORB 2503		0.06 wt%
Silica Concentration (HKS D)		0.04 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
363	0.432	0.01
403	0.458	0.02
433	0.476	0.03
463	0.493	0.03
483	0.503	0.04
523	0.523	0.07
543	0.532	0.09
563	0.541	0.12
583	0.550	0.15
613	0.562	0.16
643	0.574	0.24
673	0.585	0.42
693	0.592	0.53
723	0.603	0.71
753	**0.612**	**441**
783	**0.621**	**479**
893	**0.652**	**522**
973	**0.671**	**568**
1133	**0.704**	**603**
1233	**0.721**	**638**
1343	**0.738**	**662**

Surfactant - EMSORB 2503		0.07 wt%
Silica Concentration (HKS D)		0.03 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
363	0.432	0.01
403	0.458	0.02
433	0.476	0.02
463	0.493	0.03
483	0.503	0.03
523	0.523	0.05
543	0.532	0.06
563	0.541	0.08
583	0.550	0.15
613	0.562	0.2
643	0.574	0.23
673	0.585	0.28
693	0.592	0.32
723	0.603	0.44
753	0.612	0.52
783	**0.621**	**391**
893	**0.652**	**492**
973	**0.671**	**518**
1133	**0.704**	**571**
1233	**0.721**	**607**
1413	**0.748**	**650**

Surfactant - EMSORB 2503		0.08 wt%
Silica Concentration (HKS D)		0.02 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
363	0.432	0.01
403	0.458	0.01
433	0.476	0.01
483	0.503	0.01
523	0.523	0.01
583	0.550	0.01
643	0.574	0.01
673	0.585	0.01
723	0.603	0.17
753	0.612	0.23
783	0.621	0.31
813	0.630	0.47
853	0.641	0.5
893	0.652	0.56
933	**0.662**	**429**
973	**0.671**	**474**
1133	**0.704**	**540**
1233	**0.721**	**593**
1413	**0.748**	**632**

Surfactant - EMSORB 2503		0.09 wt%
Silica Concentration (HKS D)		0.01 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
79	0.139	0.01
89	0.153	0.01
109	0.182	0.01
129	0.208	0.01
137	0.221	0.01
157	0.245	0.01
177	0.268	0.01
197	0.290	0.01
207	0.300	0.01
237	0.329	0.01
267	0.356	0.01
287	0.373	0.01
307	0.389	0.01
327	0.404	0.01
363	0.432	0.01
403	0.458	0.01
433	0.476	0.01
483	0.503	0.01
523	0.523	0.01
583	0.550	0.01
643	0.574	0.01
673	0.585	0.01
723	0.603	0.01
753	0.612	0.01
783	0.621	0.01
813	0.630	0.01
853	0.641	0.04
893	0.652	0.11
933	0.662	0.18
973	0.671	0.25
1023	0.682	0.85
1073	0.692	1.07
1133	**0.704**	**553**
1233	**0.721**	**606**
1413	**0.748**	**663**

Appendix A-2: Experimental Data Points for Oil B, Viscosity: 64.5mPa.s

***No Stabilizer Added*, Oil-Water Emulsion System**

Surfactant-Solids Concentration		0.0 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
70	0.125	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	**0.225**	**139.3**
160	**0.249**	**152.1**
180	**0.271**	**171.5**
200	**0.293**	**201.6**
210	**0.303**	**212**
230	**0.323**	**237.1**
270	**0.359**	**272.1**
290	**0.375**	**297**
330	**0.406**	**317**
360	**0.430**	**354**
400	**0.456**	**370**
430	**0.474**	**393**
490	**0.507**	**424**
530	**0.526**	**438**
600	**0.557**	**483**
640	**0.573**	**493**
730	**0.605**	**534**
800	**0.626**	**554**
900	**0.654**	**605**
980	**0.673**	**632**
1140	**0.705**	**651**
1240	**0.722**	**675**
1470	**0.755**	**707**

EMSORB 2503 – Surfactant Only

Surfactant Concentration		0.1 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
510	0.505	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
650	0.565	0.01
670	0.573	0.01
700	0.583	0.01
730	0.593	0.01
770	0.606	0.01
800	**0.615**	**403.2**
820	**0.621**	**438.9**
930	**0.650**	**487.1**
1030	**0.673**	**527**
1190	**0.704**	**576**
1290	**0.721**	**603**
1400	**0.737**	**649**

Surfactant Concentration		0.05 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	0.505	0.01
530	0.515	0.01
550	**0.524**	**164.5**
570	**0.533**	**185.9**
590	**0.541**	**216.5**
620	**0.554**	**254.9**
670	**0.573**	**297.1**
770	**0.606**	**360**
820	**0.621**	**384**
930	**0.650**	**426**
1030	**0.673**	**477**
1190	**0.704**	**513**
1290	**0.721**	**556**
1400	**0.737**	**610**

Surfactant Concentration		0.03 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
400	0.444	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
460	**0.479**	**183.5**
470	**0.485**	**194.5**
490	**0.495**	**225.7**
510	**0.505**	**251.2**
550	**0.524**	**284.6**
620	**0.554**	**308**
670	**0.573**	**345**
770	**0.606**	**387**
820	**0.621**	**411**
930	**0.650**	**461**
1030	**0.673**	**507**
1190	**0.704**	**551**
1290	**0.721**	**581**
1420	**0.740**	**624**

Surfactant Concentration		0.02 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	0.405	0.01
360	0.419	0.01
370	0.425	0.01
380	0.432	0.01
400	**0.444**	**87.4**
410	**0.451**	**108.9**
450	**0.474**	**148.7**
510	**0.505**	**177.5**
550	**0.524**	**219.8**
620	**0.554**	**271.5**
670	**0.573**	**309**
770	**0.606**	**342**
820	**0.621**	**381**
930	**0.650**	**407**
1030	**0.673**	**465**
1190	**0.704**	**507**
1290	**0.721**	**547**
1460	**0.745**	**612**

Surfactant Concentration		0.01 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
260	0.342	0.01
270	0.351	0.01
280	**0.359**	**83.8**
300	**0.375**	**94.7**
310	**0.383**	**108.5**
320	**0.390**	**125.8**
340	**0.405**	**147.8**
370	**0.425**	**164.9**
410	**0.451**	**185.8**
450	**0.474**	**216.7**
510	**0.505**	**252.5**
550	**0.524**	**294.1**
620	**0.554**	**310**
670	**0.573**	**352**
770	**0.606**	**386**
820	**0.621**	**421**
930	**0.650**	**460**
1030	**0.673**	**501**
1190	**0.704**	**535**
1290	**0.721**	**562**
1400	**0.737**	**612**

Surfactant Concentration		0.005 wt%, EMSORB
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	**0.296**	**70.8**
220	**0.306**	**73.1**
240	**0.324**	**85.4**
270	**0.351**	**93.1**
280	**0.359**	**105.8**
300	**0.375**	**128.5**
340	**0.405**	**148.7**
370	**0.425**	**169.4**
410	**0.451**	**178.1**
450	**0.474**	**219.1**
510	**0.505**	**249.8**
550	**0.524**	**296.3**
620	**0.554**	**308**
670	**0.573**	**351**
770	**0.606**	**390**
820	**0.621**	**428**
930	**0.650**	**457**
1030	**0.673**	**503**
1190	**0.704**	**531**
1290	**0.721**	**559**
1400	**0.737**	**610**

HDK H20 (50% hydrophobic) – Silica Nanoparticle Only

Silica (H20) Concentration		1.0 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
90	0.155	0.01
130	0.209	0.01
160	0.246	0.01
210	0.300	0.01
220	0.309	0.01
230	0.319	0.01
250	0.337	0.01
270	0.359	0.01
290	0.375	0.01
300	0.383	0.01
330	0.406	0.01
350	0.420	0.01
400	0.453	0.01
430	0.471	0.01
490	0.504	0.01
530	0.526	0.01
600	0.557	0.01
620	0.565	0.01
640	0.573	0.01
670	0.584	0.01
700	0.595	0.01
730	0.605	0.01
760	0.614	0.01
800	0.626	0.01
830	0.635	0.01
860	0.643	0.01
900	**0.654**	**420**
980	**0.673**	**487**
1140	**0.705**	**509**
1240	**0.722**	**591**
1410	**0.747**	**645**

Silica Concentration (H20)		0.5 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	0.249	0.01
180	0.271	0.01
210	0.303	0.01
220	0.313	0.01
260	0.350	0.01
290	0.375	0.01
320	0.402	0.01
350	0.423	0.01
400	0.456	0.01
430	0.474	0.01
480	0.502	0.01
520	0.522	0.01
590	0.553	0.01
620	0.565	0.01
640	0.573	0.01
670	0.584	0.01
700	0.595	0.01
720	0.602	0.01
750	0.611	0.01
790	**0.624**	**410**
830	**0.635**	**429**
860	**0.643**	**451**
900	**0.654**	**471**
980	**0.673**	**511**
1140	**0.705**	**570**
1240	**0.722**	**612**
1440	**0.751**	**671**

Silica Concentration (H20)		0.4 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
510	0.505	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
640	0.561	0.01
670	**0.573**	**378**
700	**0.583**	**392**
720	**0.590**	**425**
770	**0.606**	**446**
930	**0.650**	**492**
1030	**0.673**	**550**
1190	**0.704**	**611**
1290	**0.721**	**650**
1440	**0.742**	**682**

Silica Concentration (H20)		0.3 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
490	0.495	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	**0.533**	**355**
590	**0.541**	**381**
620	**0.554**	**407**
670	**0.573**	**442**
770	**0.606**	**497**
830	**0.624**	**532**
930	**0.650**	**563**
1030	**0.673**	**592**
1190	**0.704**	**646**
1290	**0.721**	**678**
1460	**0.745**	**719**

Silica Concentration (H20)		0.25 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	0.405	0.01
360	0.419	0.01
370	0.425	0.01
380	0.432	0.01
400	0.444	0.01
410	**0.451**	**287.4**
450	**0.474**	**301**
510	**0.505**	**335**
550	**0.524**	**351**
590	**0.541**	**391**
620	**0.554**	**416**
670	**0.573**	**439**
770	**0.606**	**491**
830	**0.624**	**529**
930	**0.650**	**567**
1030	**0.673**	**601**
1190	**0.704**	**638**
1290	**0.721**	**674**
1460	**0.745**	**717**

Silica Concentration (H20)		0.2 wt%, HDK H20
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
230	0.315	0.01
240	0.324	0.01
250	0.333	0.01
260	0.342	0.01
270	**0.351**	**165.9**
290	**0.367**	**187.4**
300	**0.375**	**219.5**
310	**0.383**	**231.5**
320	**0.390**	**258.9**
340	**0.405**	**273.5**
370	**0.425**	**297.6**
410	**0.451**	**312**
450	**0.474**	**348**
510	**0.505**	**362**
550	**0.524**	**397**
620	**0.554**	**430**
670	**0.573**	**453**
770	**0.606**	**482**
830	**0.624**	**524**
930	**0.650**	**558**
1030	**0.673**	**581**
1190	**0.704**	**612**
1290	**0.721**	**655**
1440	**0.742**	**696**

Silica Concentration (H20)		0.15 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	**0.306**	**145.1**
240	**0.324**	**155.9**
270	**0.351**	**171.5**
300	**0.375**	**221.3**
340	**0.405**	**276.4**
370	**0.425**	**301**
410	**0.451**	**315**
450	**0.474**	**341**
510	**0.505**	**365**
550	**0.524**	**392**
620	**0.554**	**428**
670	**0.573**	**456**
770	**0.606**	**480**
830	**0.624**	**529**
930	**0.650**	**553**
1030	**0.673**	**576**
1190	**0.704**	**609**
1290	**0.721**	**643**
1440	**0.742**	**692**

Silica Concentration (H20)		0.1 wt%, HDK H20
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	**0.249**	**133.2**
180	**0.271**	**185.4**
210	**0.303**	**226.5**
230	**0.323**	**276.3**
270	**0.359**	**302**
290	**0.375**	**330**
330	**0.406**	**361**
350	**0.423**	**434**
400	**0.456**	**491**
430	**0.474**	**519**
490	**0.507**	**556**
520	**0.522**	**571**
600	**0.557**	**588**
640	**0.573**	**597**
720	**0.602**	**615**
790	**0.624**	**628**
900	**0.654**	**644**
980	**0.673**	**657**
1140	**0.705**	**671**
1240	**0.722**	**710**
1450	**0.752**	**768**

HDK HKS D (30% hydrophobic) – Silica Nanoparticle Only

Silica Concentration (HKS D)		3 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
90	0.155	0.01
130	0.209	0.01
160	0.246	0.01
210	0.300	0.01
270	0.359	0.01
330	0.406	0.01
400	0.453	0.01
430	0.471	0.01
450	0.482	0.01
470	0.493	0.01
490	0.504	0.01
510	0.514	0.01
530	0.526	0.01
550	0.536	0.01
580	0.549	0.01
600	0.557	0.01
620	0.565	0.01
640	0.573	0.01
670	0.584	0.01
700	0.595	0.01
730	**0.605**	**250.3**
800	**0.626**	**330**
900	**0.654**	**388**
980	**0.673**	**423**
1140	**0.705**	**476**
1240	**0.722**	**535**
1400	**0.746**	**654**

Silica Concentration (HKS D)		2 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
90	0.155	0.01
130	0.209	0.01
160	0.249	0.01
210	0.303	0.01
270	0.359	0.01
330	0.406	0.01
340	0.413	0.01
350	0.423	0.01
370	0.437	0.01
400	0.456	0.01
420	0.468	0.01
430	0.474	0.01
450	0.485	0.01
470	0.496	0.01
490	0.507	**305**
510	**0.517**	**314**
530	**0.526**	**345**
600	**0.557**	**371**
640	**0.573**	**403**
730	**0.605**	**437**
800	**0.626**	**471**
900	**0.654**	**503**
980	**0.673**	**548**
1140	**0.705**	**594**
1240	**0.722**	**618**
1490	**0.757**	**682**

Silica Concentration (HKS D)		1 wt%, HKS D
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	0.249	0.01
180	0.271	0.01
200	0.293	0.01
210	0.303	0.01
220	0.313	0.01
240	0.332	0.01
260	0.350	0.01
270	0.359	0.01
290	0.375	0.01
310	0.391	0.01
330	**0.406**	**258.3**
350	**0.423**	**275.6**
400	**0.456**	**302**
430	**0.474**	**330**
450	**0.485**	**351**
490	**0.507**	**370**
530	**0.526**	**394**
600	**0.557**	**432**
640	**0.573**	**449**
730	**0.605**	**485**
800	**0.626**	**517**
900	**0.654**	**551**
980	**0.673**	**574**
1140	**0.705**	**616**
1240	**0.722**	**649**
1460	**0.754**	**695**

Silica Concentration (HKS D)		0.5 wt%, HKS D
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	0.249	0.01
180	0.271	0.01
200	0.293	0.01
210	0.303	0.01
220	0.313	0.01
240	0.332	0.01
260	0.350	0.01
270	0.359	0.01
290	**0.375**	**249.1**
310	**0.391**	**263.3**
330	**0.406**	**289.3**
350	**0.423**	**316**
400	**0.456**	**333**
430	**0.474**	**364**
490	**0.507**	**390**
530	**0.526**	**410**
600	**0.557**	**447**
640	**0.573**	**467**
730	**0.605**	**500**
800	**0.626**	**524**
900	**0.654**	**561**
980	**0.673**	**583**
1140	**0.705**	**629**
1240	**0.722**	**654**
1460	**0.754**	**697**

Silica Concentration (HKS D)		0.3 wt%, HKS D
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	0.249	0.01
180	0.271	0.01
200	0.293	0.01
210	0.303	0.01
220	0.313	0.01
240	**0.332**	**218**
260	**0.350**	**225.4**
270	**0.359**	**230**
290	**0.375**	**252.3**
310	**0.391**	**271.4**
330	**0.406**	**305**
350	**0.423**	**321**
400	**0.456**	**341**
430	**0.474**	**364**
490	**0.507**	**397**
530	**0.526**	**416**
600	**0.557**	**434**
640	**0.573**	**477**
730	**0.605**	**511**
800	**0.626**	**535**
900	**0.654**	**569**
980	**0.673**	**587**
1140	**0.705**	**628**
1240	**0.722**	**663**
1490	**0.757**	**720**

Silica Concentration (HKS D)		0.25 wt%, HKS D
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	0.209	0.01
140	0.225	0.01
160	**0.249**	**186**
180	**0.271**	**196**
200	**0.293**	**209**
210	**0.303**	**217**
220	**0.313**	**224.8**
240	**0.332**	**236.9**
260	**0.350**	**242.5**
270	**0.359**	**258.7**
290	**0.375**	**284.7**
330	**0.406**	**317**
350	**0.423**	**354**
400	**0.456**	**376**
430	**0.474**	**389**
490	**0.507**	**405**
530	**0.526**	**429**
600	**0.557**	**455**
640	**0.573**	**486**
730	**0.605**	**505**
800	**0.626**	**568**
900	**0.654**	**576**
980	**0.673**	**608**
1140	**0.705**	**635**
1240	**0.722**	**678**
1460	**0.754**	**721**

Silica Concentration (HKS D)		0.2 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.140	0.01
90	0.155	0.01
110	0.183	0.01
130	**0.209**	**165.7**
140	**0.225**	**173.4**
160	**0.249**	**184.6**
180	**0.271**	**198.1**
200	**0.293**	**201.5**
210	**0.303**	**219.8**
220	**0.313**	**223.2**
240	**0.332**	**237.1**
260	**0.350**	**245.3**
270	**0.359**	**257.9**
290	**0.375**	**281.4**
330	**0.406**	**314**
350	**0.420**	**356**
400	**0.453**	**369**
430	**0.471**	**381**
490	**0.504**	**409**
530	**0.523**	**421**
600	**0.554**	**449**
640	**0.570**	**480**
730	**0.602**	**510**
800	**0.624**	**556**
900	**0.651**	**580**
980	**0.670**	**611**
1140	**0.702**	**633**
1240	**0.720**	**674**
1460	**0.751**	**719**

Silica Concentration (HKS D)		0.1 wt%, HKS D
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
70	0.125	0.01
90	0.155	0.01
110	**0.183**	**108.5**
130	**0.209**	**114.7**
140	**0.222**	**131.1**
160	**0.249**	**146.6**
180	**0.271**	**158.4**
200	**0.293**	**176.5**
210	**0.303**	**189.2**
230	**0.323**	**212.6**
270	**0.359**	**258.4**
290	**0.375**	**275.3**
330	**0.406**	**307**
360	**0.427**	**322**
400	**0.453**	**360**
430	**0.474**	**373**
490	**0.507**	**404**
530	**0.526**	**424**
600	**0.557**	**464**
640	**0.573**	**485**
730	**0.605**	**531**
800	**0.626**	**552**
900	**0.654**	**575**
980	**0.673**	**595**
1140	**0.705**	**650**
1240	**0.722**	**682**
1470	**0.755**	**745**

Combination – HDK H20 (50% Silica Nanoparticle) + EMSORB 2503 (surfactant)

Surfactant - EMSORB 2503		0.005 wt%
Silica Concentration (H20)		0.095 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	**0.275**	**141.5**
220	**0.306**	**164.9**
240	**0.324**	**191.8**
270	**0.351**	**219.2**
300	**0.375**	**256.9**
340	**0.405**	**290.4**
370	**0.425**	**304**
410	**0.451**	**328**
450	**0.474**	**339**
510	**0.505**	**351**
550	**0.524**	**376**
620	**0.554**	**421**
670	**0.573**	**451**
760	**0.603**	**488**
820	**0.621**	**502**
930	**0.650**	**522**
1030	**0.673**	**569**
1190	**0.704**	**607**
1290	**0.721**	**624**
1480	**0.747**	**671**

Surfactant - EMSORB 2503		0.01 wt%
Silica Concentration (H20)		0.09 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
260	**0.342**	**198.9**
270	**0.351**	**219.2**
300	**0.375**	**256.9**
340	**0.405**	**290.4**
370	**0.425**	**304**
410	**0.451**	**328**
450	**0.474**	**339**
510	**0.505**	**351**
550	**0.524**	**376**
620	**0.554**	**421**
670	**0.573**	**451**
760	**0.603**	**488**
820	**0.621**	**502**
930	**0.650**	**522**
1030	**0.673**	**569**
1190	**0.704**	**607**
1290	**0.721**	**624**
1480	**0.747**	**671**

Surfactant - EMSORB 2503		0.02 wt%
Silica Concentration (H20)		0.08 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	0.405	0.01
350	0.412	0.01
370	0.425	0.01
380	0.432	0.01
400	**0.444**	**200.4**
410	**0.451**	**245.7**
450	**0.474**	**308**
510	**0.505**	**332**
550	**0.524**	**367**
620	**0.554**	**412**
670	**0.573**	**446**
770	**0.606**	**471**
820	**0.621**	**489**
930	**0.650**	**515**
1030	**0.673**	**521**
1190	**0.704**	**549**
1290	**0.721**	**585**
1450	**0.744**	**654**

Surfactant - EMSORB 2503		0.03 wt%
Silica Concentration (H20)		0.07 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	0.405	0.01
350	0.412	0.01
370	0.425	0.01
380	0.432	0.01
400	0.444	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	**0.505**	**328**
550	**0.524**	**348**
620	**0.554**	**364**
670	**0.573**	**379**
770	**0.606**	**421**
820	**0.621**	**453**
930	**0.650**	**467**
1030	**0.673**	**502**
1190	**0.704**	**541**
1290	**0.721**	**574**
1460	**0.745**	**615**

Surfactant - EMSORB 2503		0.04 wt%
Silica Concentration (H20)		0.06 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	**0.533**	**322**
620	**0.554**	**384**
670	**0.573**	**431**
770	**0.606**	**472**
820	**0.621**	**506**
930	**0.650**	**539**
1030	**0.673**	**551**
1190	**0.704**	**582**
1290	**0.721**	**604**
1490	**0.749**	**647**

Surfactant - EMSORB 2503		0.05 wt%
Silica Concentration (H20)		0.05 wt%
Water (mL)	Water Fraction	Conductivity (mS)
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
410	0.451	0.01
450	0.474	0.01
470	0.485	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
640	**0.561**	**333**
670	**0.573**	**379**
770	**0.606**	**425**
820	**0.621**	**461**
930	**0.650**	**490**
1030	**0.673**	**513**
1190	**0.704**	**565**
1290	**0.721**	**590**
1400	**0.737**	**603**

Surfactant - EMSORB 2503		0.07 wt%
Silica Concentration (H20)		0.03 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
350	0.412	0.01
370	0.425	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
640	0.561	0.01
670	0.573	0.01
700	0.583	0.01
730	**0.593**	**366**
770	**0.606**	**391**
820	**0.621**	**457**
930	**0.650**	**490**
1030	**0.673**	**509**
1190	**0.704**	**528**
1290	**0.721**	**544**
1450	**0.744**	**588**

Combination – HDK HKS D (30% Silica Nanoparticle) + EMSORB 2503 (surfactant)

Surfactant - EMSORB 2503		0.01 wt%
Silica Concentration (HKS D)		0.09 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
140	0.219	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
230	**0.315**	**116**
240	**0.324**	**138.5**
270	**0.351**	**163.7**
300	**0.375**	**185.4**
340	**0.405**	**229.1**
370	**0.425**	**241.6**
410	**0.451**	**268.4**
450	**0.474**	**298.7**
510	**0.505**	**333**
550	**0.524**	**359**
620	**0.554**	**372**
670	**0.573**	**436**
770	**0.606**	**467**
820	**0.621**	**509**
930	**0.650**	**550**
1030	**0.673**	**578**
1190	**0.704**	**610**
1290	**0.721**	**636**
1470	**0.746**	**679**

Surfactant - EMSORB 2503		0.02 wt%
Silica Concentration (HKS D)		0.08 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
250	0.333	0.01
260	0.342	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	**0.405**	**212.3**
370	**0.425**	**235.4**
410	**0.451**	**251.3**
450	**0.474**	**284.9**
510	**0.505**	**312**
550	**0.524**	**346**
620	**0.554**	**375**
670	**0.573**	**401**
770	**0.606**	**432**
820	**0.621**	**462**
930	**0.650**	**489**
1030	**0.673**	**515**
1190	**0.704**	**562**
1290	**0.721**	**586**
1430	**0.741**	**618**

Surfactant - EMSORB 2503		0.03 wt%
Silica Concentration (HKS D)		0.07 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
310	0.383	0.01
320	0.390	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
400	0.444	0.01
410	**0.451**	**127.5**
430	**0.462**	**157.6**
450	**0.474**	**185.9**
510	**0.505**	**254.4**
550	**0.524**	**281.3**
620	**0.554**	**326**
670	**0.573**	**358**
770	**0.606**	**397**
820	**0.621**	**411**
930	**0.650**	**459**
1030	**0.673**	**522**
1190	**0.704**	**540**
1290	**0.721**	**575**
1440	**0.742**	**611**

Surfactant - EMSORB 2503		0.04 wt%
Silica Concentration (HKS D)		0.06 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
350	0.412	0.01
370	0.425	0.01
380	0.432	0.01
400	0.444	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	**0.505**	**272.1**
550	**0.524**	**301**
620	**0.554**	**338**
670	**0.573**	**369**
770	**0.606**	**427**
820	**0.621**	**452**
930	**0.650**	**475**
1030	**0.673**	**508**
1190	**0.704**	**557**
1290	**0.721**	**588**
1430	**0.741**	**624**

Surfactant - EMSORB 2503		0.05 wt%
Silica Concentration (HKS D)		0.05 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	**0.541**	**231.5**
620	**0.554**	**274.1**
670	**0.573**	**305**
770	**0.606**	**367**
820	**0.621**	**409**
930	**0.650**	**461**
1030	**0.673**	**492**
1190	**0.704**	**532**
1290	**0.721**	**570**
1440	**0.742**	**611**

Surfactant - EMSORB 2503		0.06 wt%
Silica Concentration (HKS D)		0.04 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
160	0.242	0.01
170	0.254	0.01
200	0.286	0.01
210	0.296	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
380	0.432	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
470	0.485	0.01
490	0.495	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	**0.554**	**245.3**
670	**0.573**	**297.4**
770	**0.606**	**324**
820	**0.621**	**369**
930	**0.650**	**401**
1030	**0.673**	**425**
1190	**0.704**	**467**
1290	**0.721**	**542**
1450	**0.744**	**612**

Surfactant - EMSORB 2503		0.07 wt%
Silica Concentration (HKS D)		0.03 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
220	0.306	0.01
230	0.315	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
510	0.505	0.01
530	0.515	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
640	0.561	0.01
670	**0.573**	**211.3**
770	**0.606**	**345**
820	**0.621**	**409**
930	**0.650**	**450**
1030	**0.673**	**493**
1190	**0.704**	**529**
1290	**0.721**	**540**
1480	**0.747**	**605**

Surfactant - EMSORB 2503		0.08 wt%
Silica Concentration (HKS D)		0.02 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
220	0.306	0.01
230	0.315	0.01
240	0.324	0.01
270	0.351	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
450	0.474	0.01
510	0.505	0.01
550	0.524	0.01
590	0.541	0.01
620	0.554	0.01
640	0.561	0.01
670	0.573	0.01
700	0.583	0.01
720	**0.590**	**292.3**
760	**0.603**	**320**
820	**0.621**	**382**
930	**0.650**	**411**
1030	**0.673**	**491**
1190	**0.704**	**542**
1290	**0.721**	**583**
1470	**0.746**	**643**

Surfactant - EMSORB 2503		0.09 wt%
Silica Concentration (HKS D)		0.01 wt%
Water (mL)	**Water Fraction**	**Conductivity (mS)**
0	0.000	0.01
20	0.038	0.01
40	0.074	0.01
60	0.107	0.01
80	0.138	0.01
90	0.153	0.01
110	0.180	0.01
130	0.206	0.01
150	0.231	0.01
170	0.254	0.01
180	0.265	0.01
190	0.275	0.01
220	0.306	0.01
240	0.324	0.01
270	0.351	0.01
290	0.367	0.01
300	0.375	0.01
340	0.405	0.01
370	0.425	0.01
410	0.451	0.01
430	0.462	0.01
450	0.474	0.01
510	0.505	0.01
550	0.524	0.01
570	0.533	0.01
590	0.541	0.01
620	0.554	0.01
640	0.561	0.01
670	0.573	0.01
700	0.583	0.01
720	0.590	0.01
760	0.603	0.01
790	**0.612**	**250.7**
820	**0.621**	**321**
930	**0.650**	**378**
1030	**0.673**	**419**
1190	**0.704**	**477**
1290	**0.721**	**529**
1420	**0.740**	**566**

Appendix A-3: Phase Inversion Points, Oil A; Viscosity: 22.9mPa.

EMSORB 2503 - SURFACTANT ONLY		HDK H20 (50% Hydrophobic) - SILICA NANOPARTICLE ONLY		HDK HKS D (30% Hydrophobic) - SILICA NANOPARTICLE ONLY	
Water Fraction	Surfactant Concentration	Water Fraction	Silica Concentration	Water Fraction	Silica Concentration
0.329166667	0	0.329166667	0	0.329166667	0
0.439805825	0.004	0.356	0.05	0.181666667	0.05
0.534453782	0.007	0.425301205	0.1	0.2453125	0.1
0.534453782	0.01	0.461016949	0.14	0.289705882	0.15
0.581578947	0.02	0.487096774	0.18	0.3	0.2
0.623129252	0.03	0.515736041	0.25	0.356	0.25
0.700540541	0.05	0.561983471	0.6	0.372727273	0.3
0.722222222	0.1	0.57027027	1	0.403703704	0.5
				0.451724138	1
				0.503125	2
				0.536893204	3

COMBINATION - HDK H20 (50% Silica Nanoparticle) + EMSORB 2503 (Hydrophobic Surfactant)		COMBINATION - HDK HKS D (30% Silica Nanoparticle) + EMSORB 2503 (Hydrophobic Surfactant)	
Water Fraction	EMSORB Proportion	Water Fraction	EMSORB Proportion
0.403703704	0	0.2453125	0
0.411111111	5	0.350649351	5
0.444444444	7	0.451724138	10
0.503125	10	0.536893204	20
0.532352941	20	0.562385321	30
0.57027027	30	0.581578947	40
0.60083682	40	0.6025	50
0.632192846	50	0.612195122	60
0.712643678	70	0.621428571	70
0.722222222	100	0.661702128	80
		0.703726708	90
		0.722222222	100

Appendix A-4: Phase Inversion Points, Oil A; Viscosity: 64.5mPa.s

EMSORB 2503 - SURFACTANT ONLY		HDK H20 (50% Hydrophobic) - SILICA NANOPARTICLE ONLY		HDK HKS D (30% Hydrophobic) - SILICA NANOPARTICLE ONLY	
Water Fraction	Surfactant Concentration	Water Fraction	Silica Concentration	Water Fraction	Silica Concentration
0.224719101	0	0.224719101	0	0.224719101	0
0.295774648	0.005	0.248833593	0.1	0.183028286	0.1
0.358974359	0.01	0.305555556	0.15	0.209339775	0.2
0.444444444	0.02	0.350649351	0.2	0.248833593	0.25
0.479166667	0.03	0.450549451	0.25	0.331950207	0.3
0.523809524	0.05	0.53271028	0.3	0.375161708	0.5
0.615384615	0.1	0.572649573	0.4	0.390920555	1
		0.623520126	0.5	0.50672182	2
		0.653594771	1	0.604805302	3

COMBINATION - HDK H20 (50% Silica Nanoparticle) + EMSORB 2503 (Hydrophobic Surfactant)		COMBINATION - HDK HKS D (30% Silica Nanoparticle) + EMSORB 2503 (Hydrophobic Surfactant)	
Water Fraction	Emsorb Concentration	Water Fraction	Surfactant Concentration
0.248833593	0	0.183028286	0
0.275362319	5	0.315068493	10
0.342105263	10	0.404761905	20
0.444444444	20	0.450549451	30
0.504950495	30	0.504950495	40
0.53271028	40	0.541284404	50
0.561403509	50	0.553571429	60
0.593495935	70	0.572649573	70
0.615384615	100	0.590163934	80
		0.612403101	90
		0.615384615	100

Appendix A-5: Stability Data Points, Oils A and B, Silica Nanoparticles and Surfactant

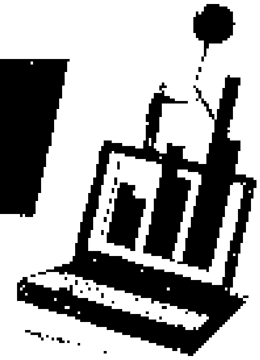
	Stabilizer/Concentration						
Time (seconds)	EMSORB 2503	EMSORB 2503	HDK H20	HKS D	HDK H20	H20:EMSORB	H20:EMSORB
	0.1 wt%	0.1 wt%	0.1 wt%	0.1 wt%	0.1 wt%	0.1:0.4	0.4:0.1
0:00:15	0	0	0	0	0	0	0
0:00:30	0	0	0	0	0	0	0
0:01:00	0	0	0	0	0	0	0
0:02:00	1	0	0	0	0	0	0
0:05:00	1	0	0	0	0	0	0
0:10:00	1	0	0	0	0	0	0
0:15:00	1	0	0	0	0	0	0
0:20:00	1	0	0	0	0	0	0
0:30:00	2	0	0	0	0	0	0
0:45:00	2	0	0	0	0	1	0
1:00:00	3	0	0	0	0	1	0
1:15:00	3	0	0	0	0	1	0
1:30:00	4	0	0	0	0	1	0
1:45:00	4	0	0	0	0	1	0
2:00:00	5	0	0	0	0	1	0
2:15:00	6	0	0	0	0	1	0
2:30:00	7	0	0	0	0	1	0
2:45:00	7	0	0	0	0	1	0
3:00:00	8	0	0	0	0	1	0
3:15:00	9	0	0	0	0	1	0
3:30:00	9	0	0	0	0	1	0
3:45:00	9	0	0	0	0	1	0
4:00:00	10	0	0	0	0	1	0
4:15:00	10	0	0	0	0	1	0
4:30:00	10	0	0	0	0	1	1
5:00:00	10	0	0	0	0	1	1
5:30:00	11	0	0	0	0	1	1
6:00:00	12	0	0	0	0	1	1
6:30:00	13	0	0	0	0	1	1
7:00:00	14	0	0	0	0	1	1
14:00:00	15	0	0	0	0	1	1
24	15	1	0	0	0	2	1
48	16	1	0	0	0	2	1
72	16	1	0	0	0	2	1
96	16	2	0	0	0	2	1
120	16	2	0	0	0	2	1
144	16	2	0	0	0	2	1
168	16	2	0	0	0	2	1

Appendix B: Material Specifications

Appendix B-1: Material Specifications, Mineral Oils

Petro-Canada

TechData



PURITY* FG WO WHITE MINERAL OILS

Introduction

Petro-Canada's PURITY* FG WO oils are ultra pure, food grade white mineral oils specially formulated for food processing, pharmaceutical and agricultural industries.

Using the patented HT purity process, Petro-Canada produces 99.9% pure, crystal clear white mineral oils – the purest in the world. Blended with a stabilizer for extended shelf life, PURITY FG WO oils are ideally suited for applications that require a straight, non-toxic white mineral oil.

PURITY FG WO oils meet the highest food industry purity standards and fit perfectly in HACCP (Hazard Analysis and Critical Control Point) and GMP (Good Manufacturing Practices) plans. They are H1 and 3H registered by NSF and n and n3 registered by the Canadian Food Inspection Agency.

Features and Benefits

- **Low volatility**
  - Minimizes consumption
- **Includes an oxidation inhibitor for stability**
  - Extended shelf life
- **Odourless and tasteless**
- **Rapidly separates from water**
- **Excellent low pour characteristics**
  - Good fluidity at low temperatures
- **Water white in colour, does not stain**
- **Fully approved for use in and around food processing areas**
  - H1 registered by NSF as a lubricant with incidental food contact for use in and around food processing areas
  - 3H registered by NSF for use as a release agent on hard surfaces to prevent food from sticking during processing
- Registered n and n3 by the Canadian Food Inspection Agency (CFIA)
- Certified Kosher and Pareve by Star K
- Certified Halal by IFANCA
- Meets United States Food and Drug Administration (FDA) regulations:
  - CFR 21, Section 172.878 White Mineral Oil
  - CFR 21, Section 178.3620 (a) - White Mineral Oil
  - CFR 21, Section 178.3570 - Lubricants with Incidental Food Contact
  - CFR 21, Section 176.170 - Components of paper and paperboard in contact with aqueous and fatty foods
- **PURITY FG WO 35 and 90 meet mineral oils, USP (United States Pharmacopoeia standards)**
- **PURITY FG WO 15 meets Light Mineral Oil, NF (National Formulary)**
- **PURITY FG WO 15 is approved by the United States Department of Agriculture (USDA) for use as a protecting oil on Shell Eggs processed in plants operating under the USDA voluntary shell egg grading program**

NSF H1, 3H

REGISTERED

- **Maintains food allergy safety**
  - Free of gluten
  - Contains no peanuts, tree nuts, or their derivatives
  - Manufactured in a facility that does not manufacture, store or otherwise handle any peanuts or tree nut product

Applications

PURITY FG WO oils may be safely used where an approved food grade or inert white mineral oil is required. General applications include direct and indirect food contact in producing, manufacturing, packing, processing, preparing, treating or packaging food. PURITY FG WO oils may also be used in cosmetics, pharmaceutical plastics and chemical processing and textile production.

Specific applications include:

- Rust and corrosion prevention for knives and cutting tables used in food preparation
- Coatings for fruits and vegetables
- Carrier and release agent for pharmaceutical capsules
- Release agents for molds and bakery pans
- Plasticizers
- Moisture resistant coatings on food packaging
- Dust suppressants
- Cleaning agent for stainless steel
- Shell egg protecting oil to retain freshness (15 grade only)

Typical Performance Data

PROPERTY	TEST METHOD	PURITY* FG WO		
		WO 15	WO 35	WO 90
Density, kg/L @ 15°C	D1298	0.847	0.855	0.872
Gravity, °API	D1298	35.4	33.9	30.6
Viscosity, cSt @ 40°C / SUS @ 100°F cSt @ 100°C / SUS @ 212°F	 D445 D445	 15 / 82 3.4 / 38	 34 / 176 5.8 / 46	 100 / 522 11.3 / 65
Viscosity Index	D2270	98	111	97
Flash Point, °C / °F	D92	180 / 356	220 / 428	250 / 482
Pour Point, °C / °F	D97	-18 / 0	-18 / 0	-12 / 10
Colour, Saybolt	D156	30	30	30

The values quoted above are typical of normal production. They do not constitute a specification.

Health and Safety

Petro-Canada PURITY FG WO White Minerals oils have no adverse effect on health, provided they are used as directed. To obtain Material Safety Data Sheets (MSDS), contact your Petro-Canada Lubricants representative, or one of Petro-Canada's TechData Info Lines.

TechData Info Lines

If you would like to know more about Petro-Canada PURITY FG WO White Mineral oils, or any other product in our complete line of quality lubricants, please contact us at:

Lubricants Head Office
Petro-Canada
2310 Lakeshore Road West
Mississauga, Ontario
Canada L5J 1K2

CERTIFIED
ISO 9001
ISO 14001
ISO/TS 16949

Canada - West . . . . Phone 1-800-661-1199
- East (English) . . . . Phone 1-800-268-5850
(French) . . . . Phone 1-800-576-1686
Other Areas . . . . Phone (416) 730-2408
E-mail . . . . lubecsr@petro-canada.ca
Internet . . . . www.petro-canada.com

Petro-Canada Europe Lubricants
The Manor, Haseley Business Centre
Warwick, Warwickshire
CV35 7LS
United Kingdom
Phone . . . . +44 (0) 2476-247294
Fax. +44 (0) 2476-247295

Petro-Canada America Lubricants
980 North Michigan Avenue
Suite 1400, #1431
Chicago, Illinois
USA 60611
Phone 1-888-284-4572
Fax. (708) 246-8994
E-mail. . . . . email@petro-canadaamerica.com

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Beyond today's standards. PETRO-CANADA*

Appendix B-2: Material Specifications, Silica Nanoparticles

HDK® H20

Pyrogenic Silica - Fumed Silica

Characteristics

Synthetic, hydrophobic amorphous silica, produced via flame hydrolysis

Special characteristics

White colloidal powder of high purity

Application

HDK® H20 is applied as a thickening and thixotropic agent in coatings, printing inks, adhesives, cosmetics and others. It is used as a reinforcing filler in elastomers, mainly silicone-elastomers. HDK® H20 acts as a free flow additive in the production of technical powders.

Processing

A good dispersion of HDK® H20 is a must to assure optimum performance.
More detailed information about the application and processing of HDK® H20 is available in our HDK-brochures and on the WACKER web site (http://www.wacker.com/hdk)

Storage

HDK® H20 has a shelf life of at least 24 months when stored in unbroken original packaging in dry storage areas. The "Best use before end" - date of each batch is shown on the product label.

If the material is kept beyond the shelf life recommended on the product label, it is not necessarily unusable, but a quality control should be performed on the properties relevant to the application.

Product data

Typical General Properties	Test procedure	Unit	Value
SiO_2-content 1)	DIN EN ISO 3262-19	%	> 99.8
density of SiO_2		g/l	2200
silanol group density		SiOH/nm²	1
electric resistivity (density 40 g/l)		[Ω cm]	> 10^{13}
BET-surface area	DIN ISO 9277/ DIN 66132	m²/g	ca. 170

Physical-chemical properties	Test procedure	Unit	Value
BET-surface area of hydrophilic silica	DIN ISO 9277/ DIN 66132	m²/g	170 - 230
Carbon content		%	ca. 1.1
pH, in 4 % dispersion 2)	DIN EN ISO 787-9		3.8 – 4.8
tamped density	DIN EN ISO 787-11	g/l	ca. 40
loss on drying 3) (2 h at 105°C)	DIN EN ISO 787-2	%	< 0.6
sieve residue, acc. to Mocker > 40 µm	DIN EN ISO 787-18	%	< 0.05
Surface modification		$-OSi(CH_3)_2-$	

1) based on the substance heated at 1000 °C for 2 h
2) 1:1 mixture of water-methanol
3) ex works