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Determination of Surfactant Solution Viscosities with a Rotational Viscometer

Remelisa Esteves, Nonso Onukwuba, and Birce Dikici

Abstract

Aqueous surfactant solutions are used in engineering systems for improving boiling heat transfer. The purpose of this research is to determine the viscosities of surfactant solutions and to investigate the effect of composition on viscosity. The results obtained can possibly be used as reference for further study in the effects of surfactant solution viscosities on nucleate boiling. A rotational viscometer was used to determine the viscosities of three surfactant solutions – SLS, EH-14, and SA-9 – of various compositions at room temperature. It was discovered that the viscosities of SLS, EH-14, and SA-9 had a nearly consistent pattern as their compositions increased. The approximate maximum viscosity measured was 1.39 mPa·s for SLS, 1.52 mPa·s for EH-14, and 3.17 mPa·s for SA-9. Based on the results, it was inferred that as the composition of these surfactant increases, so does the viscosity of the solution.

Introduction

The nucleate boiling of water is important in engineering systems such as cooling equipment for electronics. Engineering systems can malfunction when overheated; thus it is important to keep their temperatures low. To prolong the service life of engineering systems, water can be used to cool the equipment for electronics within those systems. Adding surfactants in boiling water increases the number of nucleation sites and reduces wall temperature [1,2]. To understand the effectiveness of surfactants on nucleate boiling of water, it is imperative to investigate their fluid properties when mixed with water. For this study, viscosity, a fluid property, was investigated.

Viscosity is defined as fluid's resistance to flow [3]. In one-dimensional shear flow of Newtonian fluids, shear stress can be expressed by the linear relationship: where

$$\tau = \mu \frac{du}{dy} \quad (1)$$

the constant of proportionality μ is called the coefficient of viscosity or the dynamic (or absolute) viscosity of the fluid, whose unit is kg/m·s, or equivalently, N·s/m² (or Pa·s). Rate of deformation of a fluid element is equivalent to du/dy [4]. For liquids, the viscosity is approximated as

$$\mu = a10^{b/(T-c)} \quad (2)$$

where, again, T is absolute temperature and a , b , and c

are experimentally determined constants. For water, using the values $a = 2.414 \times 10^{-5}$ N·s/m², $b = 247.8$ K, and $c = 140$ K results in less than 2.5 percent error in viscosity in the temperature range of 0°C to 370°C [4]. For instance, the viscosity of water is 1.002 mPa·s at room temperature (20°C), 0.8903 mPa·s at 25°C, and 1.138 mPa·s at 15°C [5]. It can be seen from the variance in viscosity that viscosity decreases as temperature increases for most liquids. It is important that the temperatures of the surfactant solutions are kept constant to ensure consistency of results when testing the viscosity of solutions.

The objective of this research is to determine the viscosity of several surfactant solutions and to investigate the relationship between composition and viscosity. While the scope of this research is limited to determining the viscosity of surfactant solutions, the results obtained from this study can be referenced for further study in the effects of surfactant solution viscosities on nucleate boiling.

Methodology

The three surfactants are used in the experiments: Sodium lauryl sulfate (SLS), ECOSURF™ EH-14, and ECOSURF™ SA-9. SLS is an anionic surfactant used in many cleaning and hygiene products. EH-14 surfactant is biodegradable, nonionic surfactant with low aquatic toxicity. SA-9, known as a seed oil surfactant, is also a biodegradable nonionic surfactant that composed of alcohols, C6-C12, ethoxylated, and propoxylated 55-80 percent. SLS is the only solid surfactant among the other surfactants. EH-14 can be described as a clear and slippery liquid that is soluble in water, which means it

dissolves in water. The surfactant SA-9 is described as a pale yellow liquid and is water dispersible. Water dispersible means that the chemical breaks down into very minute particles in water.

EH-14 and SA-9 were chosen because they are biodegradable and environmentally friendly alternatives to SLS. Additionally, they are new surfactants, so information on them cannot be found in literature. This research aims to study their viscosities at various concentrations. SLS, on the other hand, is a commonly used surfactant. Therefore, the results of the eco-friendly surfactants were compared to those of SLS.

The measurements are performed using a Digital Display Rotary Viscometer NDJ-5S (Figure 1). A rotational viscometer is specifically chosen for the experiment because it has the advantage of operating continuously at a given shear rate [6]. Because of this advantage, a rotational viscometer is generally used when absolute viscosity needs to be measured. This device measures viscosity from a rotating cylindrical rotor, which comes in different sizes depending on the fluid. The torque created

by the rotor on the fluid is dependent on the radius of the rotor. The rotational viscometer senses the torque required to rotate the rotor at a constant speed while immersed in a fluid [7, 8]. By measuring the torque, the fluid shear stress at any point of the rotor can be found, thus viscosity can be determined.

The #0 rotor is a rotor that is used to measure liquids



Figure 1: Digital Display Rotary Viscometer NDJ-5S

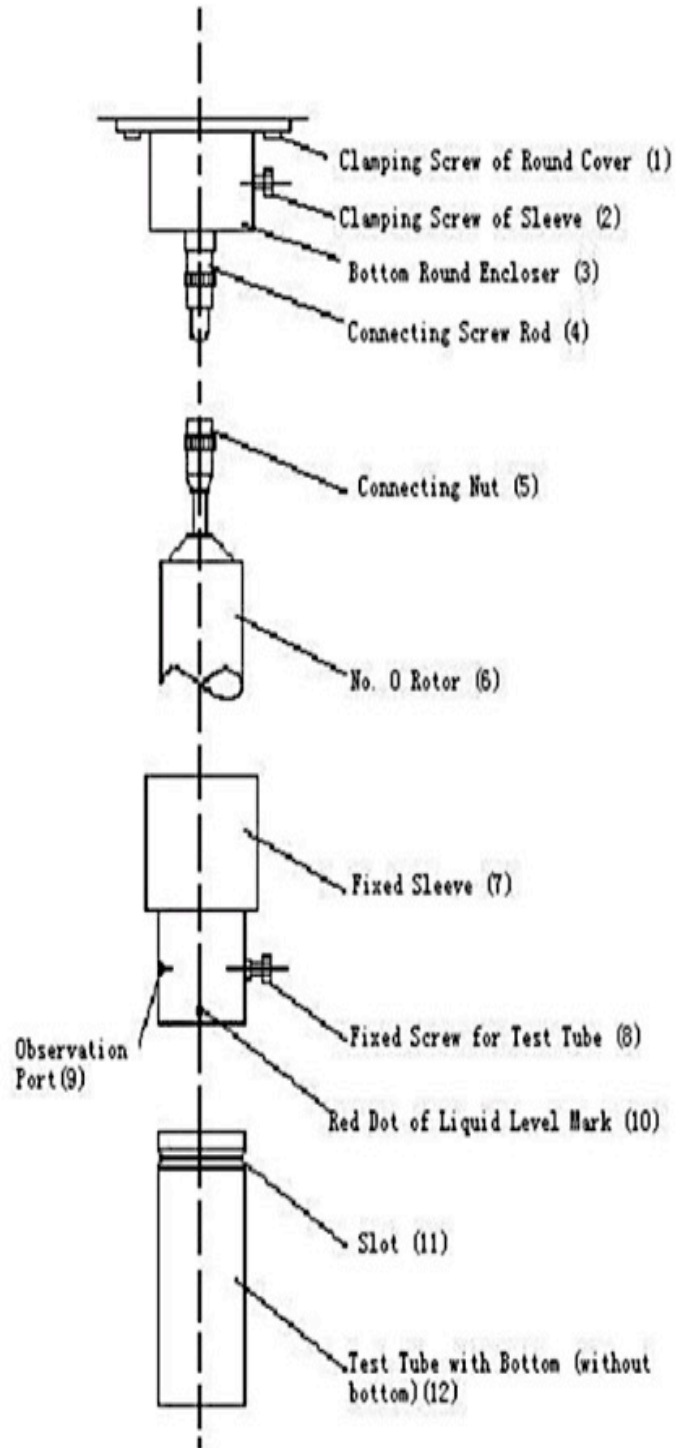


Figure 2: Diagram of #0 rotor assembly [9]

with viscosities less than 15 mPa·s. This rotor also came with a fixed sleeve, a fixed screw for test tube, a test tube with a bottom, and a test tube without a bottom. Figure 2 shows how #0 rotor and its components are assembled onto the housing of the viscometer.

To allow the rotor to make contact with the liquid, the test tube without a bottom was used. The test tube ensured that the viscometer obtained accurate measure-

ment. To avoid skewed results, the rotor should not touch the inner wall of the tube. If the rotor deflected on a certain side, then adjustments were made to move the rotor away from the inner wall of the test tube to avoid skewed results. Once the rotor was centered, water at room temperature was tested to ensure that the viscometer would measure accurately. It was found that the resulting viscosity value from the viscometer matched the expected value (1.002 mPa·s at 20°C). It was noted that, during the process of measuring a liquid, it is normal for the rotor to swing slightly within the test tube. However, if the rotor touches the inner wall of the tube while testing a liquid, the rotor would need to be readjusted.

The next step that was taken in carrying out the research was to determine the viscosity of the surfactants. A calibrated scoop aided in obtaining the correct amount of surfactant. This amount was measured out to the appropriate weight. PPM is a unit of measurement, which means parts per million.

$$ppm = 1,000,000 \frac{m_{surf}}{m_{sol}} \quad (3)$$

In Equation 3, m_{surf} is surfactant mass and m_{sol} is surfactant solution mass. For each trial, water was tested first before surfactant solutions. This procedure was followed to ensure accurate and consistent data. The mass of water that was used to mix all surfactants was a constant 400 g throughout the experiment. The uncertainty of the rotational viscometer is ± 5 percent for Newtonian liquids. Since water is a Newtonian liquid, it was expected that the experimental viscosity of water would measure as 1.002 ± 0.05 mPa·s. Tools of measurement ensured consistent measurements of water and surfactants. A hot plate and magnetic stirrer allowed thorough mixing of the surfactant solutions. After mixing, the viscosities of the surfactant solutions were measured with the viscometer. This procedure was repeated in order to verify and compare results between two trials. After each trial, the rotor and its casings were detached and washed out. The beakers and other equipment were also washed out and dried to avoid skewed data. This process was carried out for the remainder of the experiments.

Results

Figure 4 shows the viscosity measurements of the SLS solution with the corresponding compositions from trials 1 and 2.

Figure 5 shows the viscosity measurements of the EH-14 solution with the corresponding compositions from trials 1

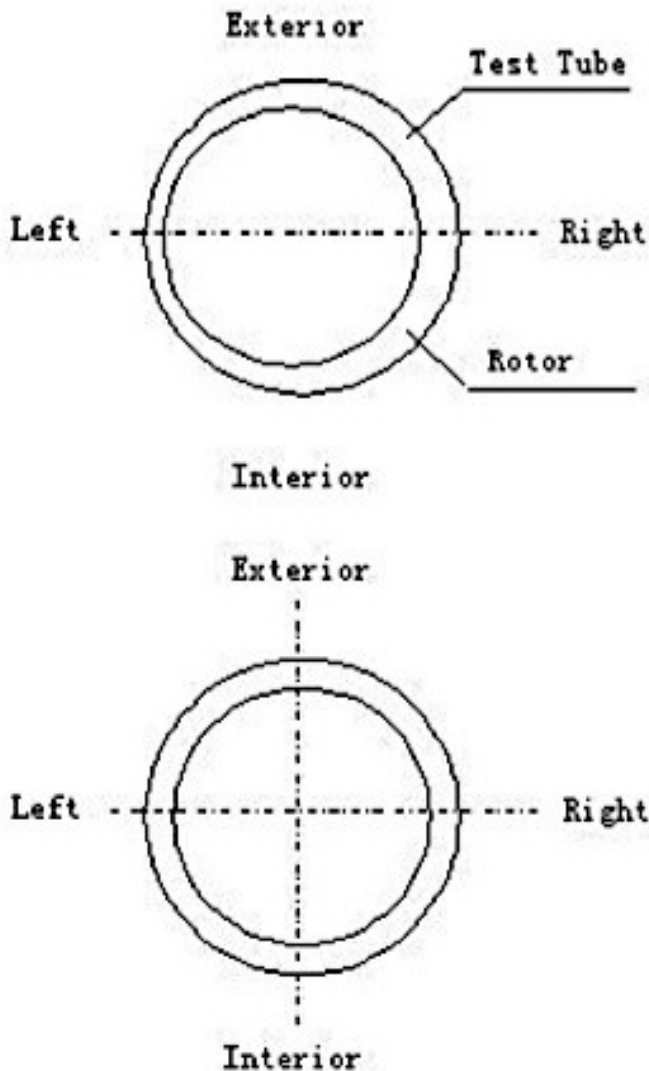


Figure 3: Diagram of #0 rotor deflection check [9]

ment. A small mirror allowed clear viewing of the rotor within the bottomless tube to see whether the rotor deflected on a certain side. Figure 3 shows an example of this deflection (top) and the correct position of the rotor (bottom).

If the rotor deflects on a certain side, then adjustments need to be made to move the rotor away from the inner

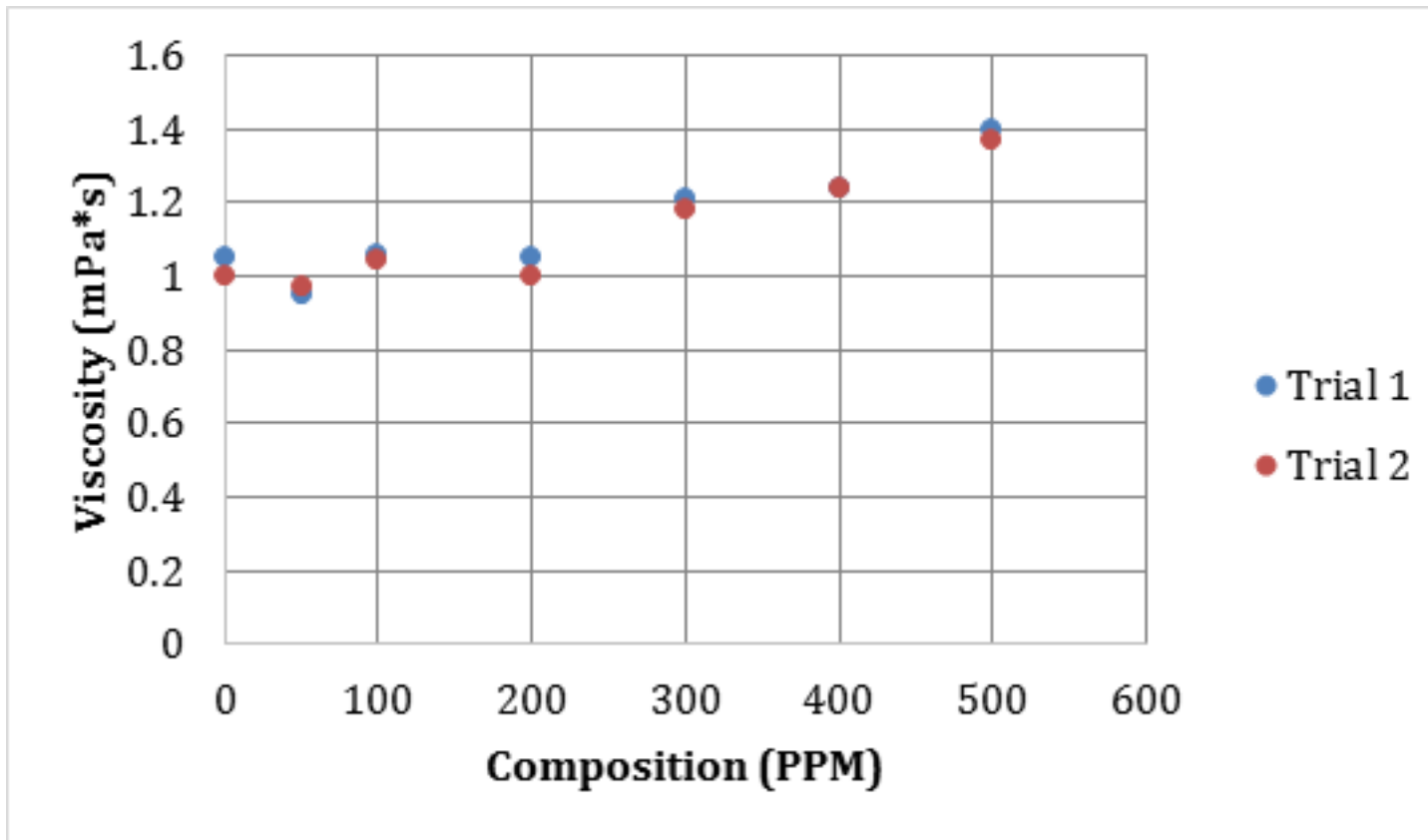


Figure 4: SLS solution viscosities with increasing composition

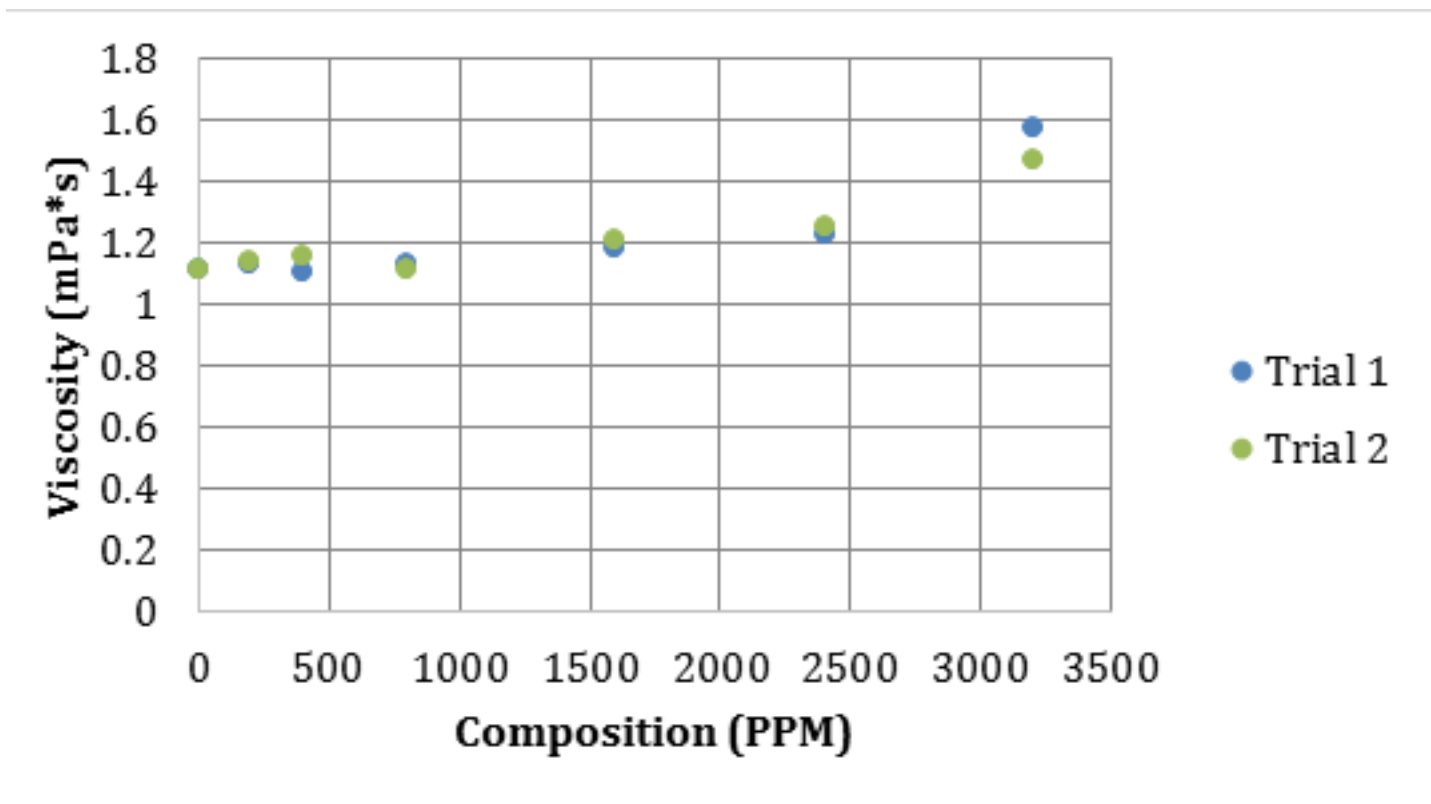


Figure 5: EH-14 viscosities with increasing composition

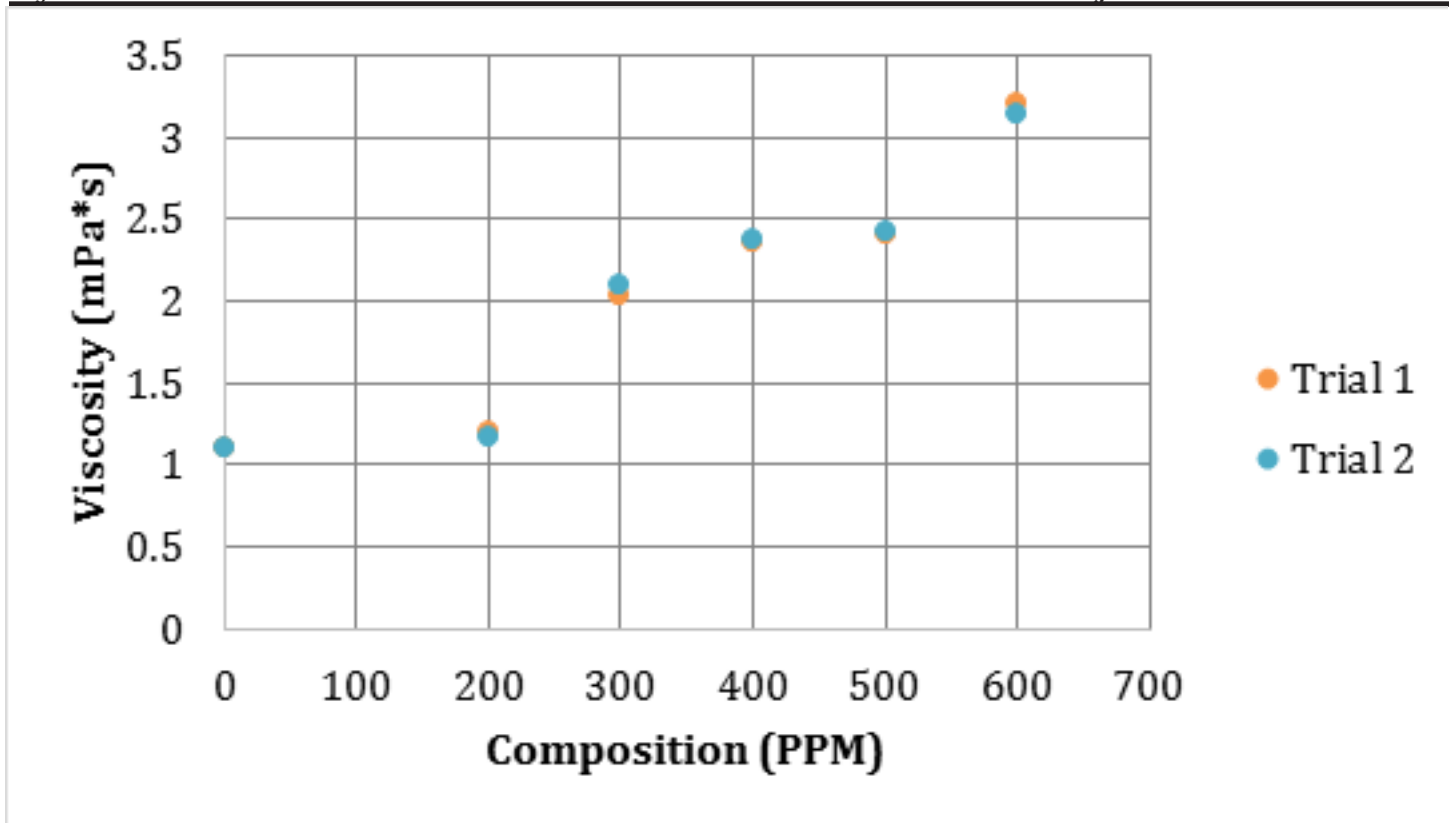


Figure 6: SA-9 viscosities with increasing composition

and 2.

Figure 6 shows the viscosity measurements of the SA-9 solution with the corresponding compositions from trials 1 and 2.

Discussion and Error Analysis

It was observed that the viscosity slightly increased as the composition of SLS increased. Figure 4 showed a steady increase in viscosity as the composition of EH-14 increased. For SA-9, it was observed that both trials follow a very similar pattern to each other. Figure 6 shows a significant increase in viscosity between 200 PPM and 300 PPM and between 500 PPM and 600 PPM. The SA-9 solution showed the most significant increase in viscosity out of all of the solutions.

Surfactant solution's Newtonian or Non-Newtonian behavior also affects when the viscosity values measured at increased concentrations. If the solution viscosity does not change significantly at higher concentrations, that means the solution reveals the Newtonian fluidic behavior [10]. Viscosity of Non-Newtonian surfactant solutions is increased with the surfactant concentrations [10].

To verify the consistency in the measurements, the percentage differences were determined.

$$\%diff. = \left| \frac{\mu_{r1} - \mu_{r2}}{\frac{\mu_{r1} + \mu_{r2}}{2}} \right| * 100\% \quad (4)$$

In Equation 4, μ_{r1} is the viscosity of a surfactant solution from trial 1 and μ_{r2} is the viscosity of a surfactant solution from trial 2. Table 1, 2 and 3 (Appendix) shows all of the percentage differences for the SLS, EH-14 and SA-9 solutions. The percentage differences fell within 5 percent for SLS, within 7 percent for EH-14, and within 3 percent for SA-9, which indicates that the viscosities from each trial were nearly consistent. Next, the percentage errors of the viscosities of each solution at 0 PPM were calculated because they slightly deviated from the theoretical viscosity of water at room temperature. Equation 5 was used to perform this calculation.

$$\%error = \left| \frac{\mu_{exp} - \mu_{theory}}{\mu_{theory}} \right| * 100\% \quad (5)$$

μ_{exp} is the measured viscosity of water, and μ_{theory} is the theoretical viscosity of water (1.002 mPa*s at 20°C).

Percentage errors of water viscosity measurements from each trial of each surfactant test show that the error varied from 0.2 percent to 10.7 percent. This is because water viscosity at 20°C is 1.002 mPa*s and reduces 23

percent in only 10°C temperature difference. Table 4 shows the percentage errors for each surfactant test.

The test with the lowest average percentage error was the SLS test, which indicated that the measurement of the viscosity of water was very close to accurate. On the other hand, the EH-14 test had the highest average percentage error. In general, the percentage errors in Table 4 show that there were fluctuations in the measurements.

In this study, there were several sources of errors that could have led to skewed and inaccurate data. One source of error for this experiment was the fact that mass scale that was used in measuring the masses of the surfactant and the water had a maximum mass rating of 300 g. As the water had to be a constant 400 g, a mass of 250 g was always obtained first and then another mass of 150 g of water had to be added to it. In transferring the water masses between beakers, some droplets were left behind which could have led to incorrect readings. In transferring the weighed surfactant masses into the beakers of water, it was always difficult in successfully transferring all the surfactant into the beaker. It was especially difficult working with SA-9 due to its property of being water dispersible. This made it difficult to rinse out the surfactant from the small measurement cups into the beaker. When measuring water, it was observed that the experimental viscosity values slightly deviated from the theoretical value of 1.002 mPa·s at room temperature. As mentioned in the methodology section, the uncertainty of the rotational viscometer is a contributor to this error. Tables 2 and 3 in the appendix section show that the recorded values for water went slightly higher than expected uncertainty range. Temperature was the likely contributor to this error, along with the uncertainty of the viscometer, since viscosity is sensitive to temperature changes. The percentage error had to be approximately 10 percent or less to consider the experimental viscosity as reasonable. On the other hand, for Non-Newtonian fluids, a rheometer might be a more convenient instrument to measure the fluid flow in response to applied forces. It is not known if the higher concentration solutions of SLS, EH-14, and SA-9 present Newtonian or Non-Newtonian behavior.

Conclusion

From the data presented, it was observed that the viscosities of each surfactant solution increased with an increase in its composition. Although this was an expected result, the plots show different patterns. The SA-9 surfactant in particular, had the steepest slope out of the

three surfactants. Another observation was the range of values in which the viscosity increase occupies. Both the SLS and EH-14 surfactants occupied viscosity ranges of between 0.9 mPa·s and 1.6 mPa·s. SA-9, however, occupied a range of 1.10 mPa·s and 3.2 mPa·s. It could be because of surfactants' critical micelle concentration (CMC). If CMC is exceeded, the viscosity is increased more rapidly. Also, SA-9 is water dispersible. The suspended particles in the solution could be the reason for its higher viscosity, as the solution is not a uniform and homogenous one. This might be the reason of the higher viscosity values for SA-9 at higher concentrations.

The findings of this research provide a better understanding of the viscous behavior of surfactant solutions. In the future, the relationship of surface tension with surfactant concentration will be investigated for various surfactants. Research will be conducted to study how fluid properties affect boiling heat transfer. If some biodegradable surfactants show favorable results in comparison to SLS, then they can possibly be used as alternative sources for improving boiling heat transfer.

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Authors

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Remelisa Esteves is an undergraduate student of Embry-Riddle Aeronautical University (ERAU) who is currently a senior in aerospace engineering with a specialization in aeronautics and a minor in applied mathematics. She is involved in school clubs, including Sigma Gamma Tau (SGT) and Kappa Mu Epsilon (KME). She worked on campus as a teaching assistant for Calculus and Analytical Geometry I for Engineers and a mathematics tutor. Although Remelisa studies aerospace engineering, she takes interest in Fluid Mechanics. Currently, she is studying the fluid properties of surfactant solutions. Through research, she investigates the application of surfactant solutions to engineering systems.

Nonso Onukwuba

Nonso Onukwuba is a senior at Embry-Riddle Aeronautical University, scheduled to graduate in the spring semester of 2016. He is currently pursuing a Bachelor of Science degree in Aerospace Engineering with a focus on the Aeronautics track. He is a member of AIAA, Catholic Students Association as well as the African Students Association, where he served dutifully as the financial secretary. In addition to Aerospace Engineering, Nonso is very much involved in the Mechanical Engineering Department, where his interests in Fluid mechanics can be observed through the research projects he is an active participant in.

Dr. Birce Dikici

Dr. Dikici is an assistant professor at Embry-Riddle Aeronautical University. She obtained both her MSME and Ph.D. from Texas Tech University upon receiving her BSME from Gazi University, Turkey. Dr. Dikici has numerous journal and conference proceedings on energy generation, boiling, and clean energy systems. She designed various experimental systems and developed several diagnostic methods for characterization of Aluminum nanoparticle burning and brought a number of

analytical approaches to model energy propagation.

Dr. Dikici is also ASME student section advisor at Embry-Riddle Aeronautical University. She encourages mechanical engineering students to become involved in their ASME student section by arranging activities.

Appendix

Table 1: Summary of SLS solution tests

Composition (PPM)	Viscosity Trial 1 (mPa·s)	Viscosity Trial 2 (mPa·s)	Percentage Difference
0 (Tap water)	1.05	1.00	4.88%
50	0.95	0.97	2.08%
100	1.06	1.04	1.90%
200	1.05	1.00	4.88%
300	1.21	1.18	2.51%
400	1.24	1.24	0.00%
500	1.40	1.37	2.17%

Table 2: Summary of EH-14 solution tests

Composition (PPM)	Viscosity Trial 1 (mPa·s)	Viscosity Trial 2 (mPa·s)	Percentage Difference
0 (Tap water)	1.11	1.11	0.00%
200	1.13	1.14	0.881%
400	1.10	1.15	4.44%
800	1.13	1.11	1.79%
1600	1.18	1.21	2.51%
2400	1.22	1.25	2.43%
3200	1.57	1.47	6.58%

Table 3: Summary of SA-9 solution tests

Composition (PPM)	Viscosity Trial 1 (mPa·s)	Viscosity Trial 2 (mPa·s)	Percentage Difference
0 (Tap water)	1.10	1.10	0.00%
200	1.20	1.17	2.53%
300	2.04	2.10	2.90%
400	2.35	2.38	1.27%
500	2.40	2.43	1.24%
600	3.20	3.14	1.89%

Table 4: Percentage errors of water viscosity measurements from each trial of each surfactant test

Surfactant	Percentage Error Trial 1	Percentage Error Trial 2
SLS	4.79%	0.200%
EH-14	10.7%	10.7%
SA-9	9.78%	9.78%