Full Paper

FOAM STABILITY PERFORMANCE ENHANCED WITH RICE HUSK ASH NANOPARTICLES

Chuah Kai Jie*, Mohd Zaidi Jaafar, Wan Rosli Wan Sulaiman

Department of Petroleum Engineering, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
chuahkj15@spe.petroeleum.utm.my

Abstract

The objective is to study the effectiveness of using nano-sized rice husk ash (nano-RHA) as an additive to stabilize normal gas generated surfactant foam used in enhanced oil recovery. To decrease the size of the RHA into nano range, planetary ball mill was used in both dry grinding and wet grinding. Different surfactants including anionic and non-ionic were used to study the polydispersity index of the dispersion and the hydrodynamic diameter using dynamic light scattering in dilute suspension. Besides, the nano-RHA was characterized using FESEM, EDX, XRD and the change in specific area after grinding process was studied using BET. The foamability of different surfactants were then studied using minor concentration of nano-RHA. Next, the concentration of the nano-RHA was varied from 0.1wt% to 0.9wt% in normal gas bulk foam stability test using the suitable surfactant, the texture of foam was observed as well. Moreover, the effect of oil on bulk foam was also studied. Finally, the result was compared using pure silica nanoparticles as the foam addictive at the same variation of concentrations. Dispersion stability tests showed that both anionic and non-ionic surfactants can be used to disperse nano-RHA in water. Furthermore, in the presence of 0.9wt% of nano-RHA concentration, the bulk foam stability test results revealed that the sodium dodecyl sulfate bulk foam half-life increased by 17.9% without the presence of oil, and gave an increment of 20.7% half-life in the presence of oil. Therefore, the study showed a potential of utilizing nano-RHA in stabilizing bulk foam.

Keywords: Foam stability, surfactant, EOR, nano-rice husk ash, ball-milling

Abstrak

Projek ini mengkaji efisiensi abu sekam padi nano (nano-RHA) sebagai bahan pengstabilan busa surfaktan yang diaplikasikan dalam teknik perolehan minyak tertingkat (EOR). Untuk menghasilkan partikel dalam nano saiz, proses pengilangan bola dibuat dalam keadaan kering dan basah. Pelbagai surfaktan termasuk ionik dan anionik digunakan untuk mengukur index penyebaran larutan dan diameter hidrodinamik partikel diukur menggunakan cahaya dinamik berselerak dalam larutan cecair surfaktan. Nano partikel tersebut juga dicirikan dengan FESEM, EDX, XRD dan perubahan area khusus partikel selepas pengilangan juga diukur dengan BET. Kebusaan jenis surfaktan yang berlainan dikaji menggunakan kepekatan nano-RHA yang kecil. Selepas itu, kepekatan nano-RHA diuji dari 0.1wt% hingga 0.9wt% dalam busa surfaktan gas normal yang bersesuaian, malahan tekstur busa juga diperhatikan. Tambahan pula, kesan minyak terhadap kestabilan busa juga dikaji. Akhirnya, prestasi kestabilan busa yang ditambah nano-RHA diperbandingkan dengan busa yang ditambah nano-silika. Ujian kestabilan berselerak menunjukkan bahawa kedua-dua surfaktan ionik dan anionik sesuai digunakan untuk melarutkan nano-RHA dalam air. Selain itu, kestabilan busa surfaktan sodium dodecyl sulfate tanpa minyak meningkat sebanyak 17.9% manakala meningkat sebanyak 20.7% dalam keadaan berminyak apabila ditambah dengan 0.9%wt nano-RHA. Kesimpulannya, kajian ini menunjukkan potensi nano-RHA sebagai penstabil busa surfaktan.

Kata kunci: Kestabilan busa, surfaktan, EOR, abu sekam padi nano, pengilangan bola

1.0 INTRODUCTION

The total volume of conventional oil discovered in year 2016 plunged to the lowest annual yield in the six decades, for a merely 9 billion barrel oil equivalent (bnBOE). Besides, it also marked the sixth consecutive year of decline [1]. Despite the recent global crude oil price crisis started in year 2015, there were only six times since year 2000 in which the industry has delivered more than 30 bnBOE in a single year. The recent oil discovery performance becomes the concern and the industry is conceding the necessity to address the declining exploration in technical and economic performances. Hence, it is crucial for the industry to recover considerably more oil from the current producing assets when the challenge in making consequential new discoveries continues to rise. It is estimated that even a 5% increase in the average global recovery is comparable to the new reserves of all the future exploration activities [2]. Meanwhile, enhanced oil recovery (EOR) has been identified as the key effort to further improve oil recovery from the remaining 60% or more of the oil after the secondary recovery process. Currently, EOR contributes about 3% of the worldwide production [3].

Miscible gas flooding increases from 118 projects in 2004 to 174 projects in 2014, becoming the most widely implemented EOR technique in worldwide [4]. Gas flooding provides a higher microscopic sweep efficiency compared to water-flooding. However, the efficiency is affected by viscous instability, reservoir heterogeneity and gravity segregation [5]. A need for mobility control in gas flooding has led to the use of foam for sweep improvement and profile modification. Foam is a two-phase fluid system in which the gas phase is discontinuous, separated by thin liquid film known as lamellas [6]. Unlike gas flooding which is influenced by viscous fingering and gravity override, foam has great specific gravity-independent properties. With the controlled mobility using foam, the gas can be channelled from high-permeability areas to the low-permeability areas. Thus, enabling the injected gas to reach the poorly swept sections of the reservoir. Also, foams performs better in controlling the fingering problem as compared to WAG [7]. The key parameter to define a good quality of foam is the foam stability [8]. In other words, foam needs to possess a better lifetime depending on its purpose of applications, usually it is desired to be stable over the distance of propagation through the well.

In foam flooding, surfactants are generally used to generate and stabilize the foam lamellas by adsorbing themselves to the fluid interface. Foamability and the foam stability are enhanced with increasing surfactant concentration [9]. To produce the stable foams, the concentration used should be at least maintained at the surfactant critical micelle concentration (CMC). Surfactant foam, however, is unstable when in contact with oil [10]. Moreover, surfactant-stabilized foam is also thermodynamically inferior [11] and prone to destabilization in harsh conditions such as high salinity [12] and high reservoir temperature. Consequently, greater amount of surfactants as compared to laboratory scale is required to produce surfactant-stabilized foam for mobility control [13]. Meanwhile, the use of solid particles in nano-size provides solution to the problems discussed above.

Khajehpour *et al.* (2016) reported nanoparticles-stabilised-foam is more stable than surfactant-stabilised-foam [14]. Compared to surfactant molecules, due to the higher adsorption energy of the nanoparticles, they are able to adsorb irreversibly at the fluid interface [15]. Besides, they are able to stabilize foam even under extreme temperature and high salinity conditions [16]. Hydrophobicity is known to be the key property of nanoparticles because it has significant effects on their reaction behaviours [17]. Generally, nanoparticles surface is coated to alternate the surface chemistry and it will influence the effects of the nanoparticle core. Polyethylene glycol (PEG)-coated hydrophilic silica nanoparticles generated stable supercritical CO_2 water foam in glass beads [18]. On the other hand, Worthen *et al.* (2013) reported partially hydrophobic nanoparticles performed more effectively than the PEG-coated ones as foam stabilizers [19]. It is commonly surface-active or modified nanoparticles were better foam stabilizers than surfactants. However, nanoparticles available at commercial are usually non-surface active with extreme hydrophobicity [20]. Surface modification of nanoparticles using surfactants has shown potential method to stabilize foams. The synergy between nanoparticles and surfactants has been studied over years. Both Zhang *et al.* (2008) and Cui *et al.* (2010) reported the stabilization of aqueous foams using a mixture of non-surface active nanoparticles and surfactants [21], [22]. Furthermore, Binks *et al.* (2015) even generated ultrastable foam with more than one-year time foam half-life using $CaCO_3$ nanoparticles and sodium stearoyl lactylate (SSL) at high concentration [23]. Using fly ash nanoparticles, Singh *et al.* (2015) reported the synergy with anionic surfactant which enhanced foam stability in porous media [24]. Besides, Wong (2017) achieved remarkable stable sodium dodecyl sulfate (SDS) bulk foams with the addition of fly ash nanoparticles [25].

Rice husk (RH), an agricultural waste is vastly available in rice producing countries such as China, India and Indonesia. Incineration of RH from the RH biomass power plant produces rice husk ash (RHA) as waste product. According to World Rice Statistics (2014), the total RHA world production increased from 28 Mt in 2010 to 29.6 Mt in 2014. India alone accounted for 20.6% (6.1 Mt) of RHA in 2014, second highest after China 27.9% (8.3 Mt). Inappropriate way of disposal will undoubtedly cause long term environmental issues due to the low bulk density of RHA [26]. Positively, RHA is used in coatings, cement industry, insulator and electronics [27]. The laboratory synthesis of SiO_2 nanoparticles (SiO_2-NP) from RHA

was also studied by Thuadaji and Nuntiya (2008) [28]. However, strong acid leaching pre-treatment of RH, is significantly hazardous to environment and human life, and results in an increase of the SiO_2-NP process cost.

The feasibility of using RHA-nanoparticles (RHA-NP) in EOR application, precisely in stabilizing surfactant foams should be studied. Therefore, this paper establishes a novel method to use RHA-NP as an additive to stabilize surfactant foams. Without using any chemical pre-treatment, the size range of RHA was decreased by planetary ball mill grinding. The importance of this study will contribute another effort of utilizing the sustainable use of waste materials, besides providing an idea of the possibility to substitute hydrophilic SiO_2-NP (without surface modification) with RHA-NP since SiO_2 nanoparticles are commonly used in EOR application and they are considered one of the best nanoparticles (with dichlorodimethyl silane surface coating) to stabilize foam [29].

The three main objectives in this study are as followed:
a. To establish a novel study of the stability performance of rice husk ash nanoparticles (RHA-NP) in surfactant air foam.
b. To compare the performances of surfactant air foam stabilized by RHA-NP and hydrophilic SiO_2 nanoparticles (SiO_2-NP).
c. To study the stability performance of RHA-NP surfactant air foam in the presence of oil, and without oil.

2.0 METHODOLOGY

2.1 Materials

Rice Husk Ash (RHA)

RHA was obtained from a rice mill (*Kilang Beras Bagan Serai Sdn. Bhd.*, Perak, Malaysia). The as-received RHA (AR-RHA) was physically black in colour with some grey particles (Figure 1, left). It was due to incomplete carbon combustion during the incineration of RH [30]. The AR-RHA was sieved (AS200; Retsch, Germany) and the average size obtained was at a range between 88µm to 105µm. It was then treated under 700°C for 4 hours using an electric furnace (Thermolyne 30400 Laboratory Furnace; Barnstead, United States). This step was to reduce the carbonaceous materials present in the samples, thus increasing the relative amount of silicon dioxide content [30]. The thermal-treated RHA (TT-RHA) was observed to be grey in colour with abundant white particles (Figure 1, right). Next, the TT-RHA was then milled in order to reduce its particle size (the grinding process will be further discussed in the following section). Upon getting the desired size range, it was then characterized by morphology study using FESEM along with its elemental

composition analysis by EDX (SU8000; Hitachi; Japan). Figure 2 displays the discrete and irregular shape of the RHA in nanosize. The nanoparticles tend to agglomerate. Figure 3 is the EDX analysis result of the sample. Oxygen (39.6 wt. %) and silicon (30.4 wt. %) are the two main elements in the RHA after ball milling, hence maintaining the main natural elementary composition. Besides, the phase analysis (Figure 4) was studied using XRD (SmartLab; Rigaku, Japan). It gives a curve which shows three peaks, the first peak represents zeolite, whereas the second and third peaks belong to SiO_2. Table 1 recorded the corresponding phases and their percentage. Heating under 700°C produced mainly an amorphous phase as shown by the XRD curve with a broad hump.

2.2 Preparation of Rice Husk Ash Nanoparticle (RHA-NP)

The size of the foam additives has to be small enough to avoid them from plugging the pores of the rocks in the formation, in which typically around few microns. TT-RHA was too large to be feasibly used as foam additive. Therefore, it was submitted to ball milling process in order to produce the highest degree of fineness. It was performed by a two-stage grinding process using a planetary ball mill machine (PM100; Retsch, Germany). The method of ball milling was adopted from the guide by Retsch Germany. The grinding process involved in both dry and wet medium. First, dry grinding was performed to get a homogenous size of TT-RHA. The 250 mL tungsten carbide (WC) grinding jar was loaded with 66.7% by volume of WC mill balls (approx. 150 mL, measured using a measuring cylinder), of which 3 mm in diameter; and 33.3% by volume of TT-RHA (approx. 83 mL). It was grinded for one hour at a speed of 450 rpm. Dry grinding was intended to achieve a more homogenous particle size and to reduce the size above the average distribution. The second stage grinding was performed in wet medium to achieve nano range. To prevent the agglomeration of the particles, ethanol was added as a dispersing agent. Ethanol was added until it covered the ash and the balls mixture. The ash and the mill ball volume ratio was kept constant. Wet grinding was run for four hours at a speed of 450 rpm. The samples were then collected and dried in an oven under 90°C for at least 15 hours. Eventually, the size of the TT-RHA after wet grinding was determined by hydrodynamic light scattering using particle size analyzer (Zetasizer Nano ZS; Malvern Instrument, United Kingdom). The result gave d_{n50} reading of 140 nm. BET surface area analysis (3Flex; Micromeritics, United States) gave readings of 12.4506 m^2/g before grinding and 23.7660 m^2/g after grinding.
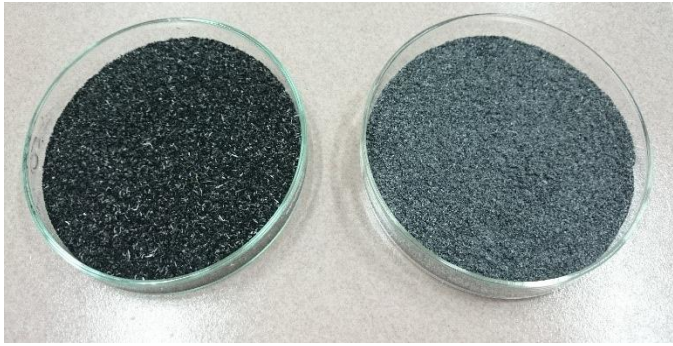
Figure 1 Left: before thermal treatment; Right: after thermal treatment (lower carbon content)
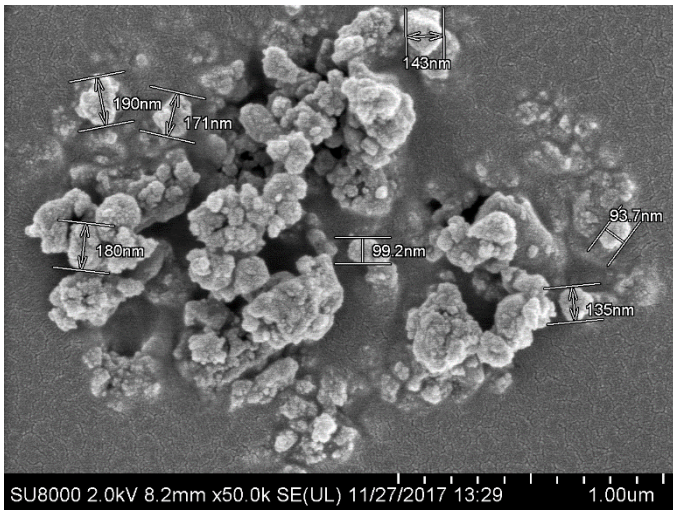

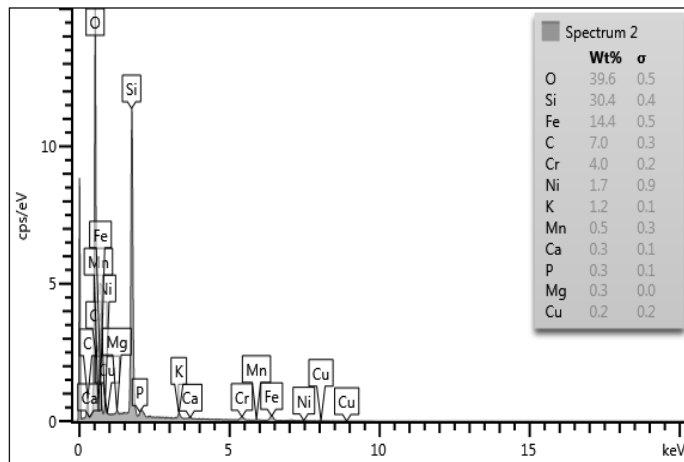**Figure 2** FESEM image of RHA-NP (in 1μm)

Figure 3 EDX analysis result of RHA-NP showing the ash comprised mainly of silicon and oxygen
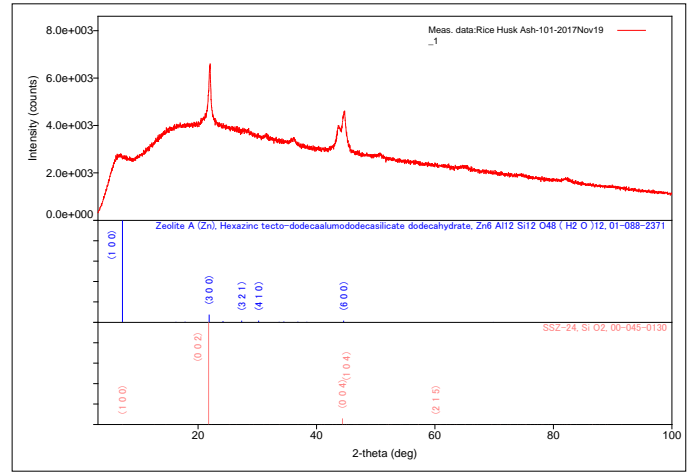

Figure 4 XRD analysis of RHA-NP

Table 1 XRD result showing the phases detected in RHA-NP

Phase name	Content (%)
Silicon dioxide (SiO_2)	99.82
Zeolite ($Na_2Al_2Si_3O_{10} \cdot 2H_2O$)	0.17
Others	0.01

2.3 Hydrophobicity Test

In order to study the characteristic of the hydrophobicity of RHA-NP, the contact angle measurement method was conducted. RHA-NP was dispersed in deionized water (DI water). Few drops of the concentrated RHA-NP dispersion was allowed to dry under room temperature on a sterile glass slide. Then, a drop of DI water was placed on the surface of the dried RHA-NP dispersion. The shape of the water droplet was captured and ImageJ software was used to analyze the contact angle.

2.4 Dispersion Stability Test

The test was conducted to identify suitable dispersant for RHA-NP. Several anionic surfactants and a non-ionic surfactant were tested. Table 2 shows the types of the surfactants used:

Table 2 Types of surfactants used in dispersion stability test

Type	Name (Label)
Anionic	Sodium Dodecyl Sulfate (SDS)
	Sodium Dodecylbenzenesulfonate (SDBS)
	Alpha Olefin Sulfonate (AOS)
Non-ionic	Triton X-100 (Octyl phenol ethoxylate)

0.5 wt% of RHA-NP was diluted in 0.2 wt% of surfactant solution. Mixture was stirred by a magnetic stirrer for an hour, followed by an hour of ultrasonication to promote dispersion stability. Samples were taken from the middle of the vials after letting three hours of settling time. Next, the samples were characterized by dynamic light scattering using particle size analyzer, Zetasizer Nano SP. Polydispersity index was also taken to measure the degree of homogeneity in respective surfactants.

2.5 Foamability Test

Compatible surfactants (0.2 wt%) from the dispersion stability test were then mixed with 0.5 wt% of RHA-NP. The foamabiliy of these surfactants in the presence of RHA-NP were studied by measuring the height of the foam produced. 4 mL of the mixture was shaken vigorously 10 times in a centrifugal tube. The height of the foam for each mixture was taken at the initial time.

2.6 Foam Stability Test

Suitable surfactant selected from the dispersion stability test and foamability test was chosen as the dispersing agent in this foam stability test. Foam stability test was conducted using dynamic foam analyzer (Krüss DFA100; Krüss, Germany). The concentration of the brine solution was kept constant at 2 wt% to simulate the formation water salinity [25] whereas the concentration of the SDS surfactant was kept at its critical micelle concentration (CMC) value. The concentrations of RHA-NP were manipulated from 0.0 wt.% (without RHA-NP) to 0.9 wt.%. It was intended to determine the trend of the effect of different RHA-NP concentrations against the SDS foam stability performance. The mixture was prepared using DI water as the solvent. The mixture was stirred using magnetic stirrer for at least 16 hours, then ultrasonicated for two hours to get better dispersion stability. The mixture was then injected carefully into the glass column of the foam analyzer using a 50 mL syringe without pre-wetting the glass above the liquid level. This is crucial as pre-wetting can affect the adhesion characteristics of the foam. The volume of each mixture injected was kept at 30 mL. Besides, the continuous phase used to generate the foam in this experiment was normal air. The normal air flow rate was set at 0.3 L/min for 15 seconds. Thus, giving a foam quality of 71.4%. In fact, stable foam can be formed through quality of 50% - 85%, while foam formed with less than 50% quality is considered relatively unstable [31]. The half-life of the foam was used to define the foam stability, in which the foam height and the time taken for the foam to disintegrate to half of its initial height were recorded using the foam analyzer software.

Using the optimum concentration of RHA-NP, the experiment was repeated with hydrophilic SiO_2-NP without surface modification (Product # 6808NM, 99.5% pure, 20 nm, non-porous,) obtained from SkySpring Nanomaterials, Inc. The SiO_2-NP was varied at the same concentrations as the ones previously used in RHA-NP. This step was done to compare the performances of both RHA-NP and commercial SiO_2-NP in stabilizing surfactant foam.

The experiment was repeated by adding oil to study the foam generation in the presence of oil. Heavy oil, n-hexadecane was used as a resemblance of crude oil. The experiment was run with RHA-NP in the presence of 10.0 v/v% n-hexadecane, C-16 (Acros Organics, 99% pure). Mixture of 0.9 wt% RHA-NP and surfactant solution was prepared using the same procedure. 27 mL of this mixture was injected into the glass column, followed by 3 mL (10 v/v%) of n-hexadecane. The oil was added carefully onto the liquid surface without contacting the glass column surface above the mixture level. The experiment was repeated with same concentration of SiO_2-NP.

Moreover, the foam is also characterized by the foam structure, taken by the camera of the dynamic foam analyzer, Krüss DFA100. The materials and formulations used were summarized as shown in Table 3.

Table 3 Materials and formulations used in the foam stability test

Material	Function	Composition
Deionised water (DI water)	As liquid solvent	80 mL
Sodium chloride (NaCl)	As brine	2 wt.%
Sodium dodecyl sulfate (SDS)	As surfactant	0.23 wt.% (CMC value)
Rice husk ash nanoparticles (RHA-NP)	As foam additives	0.1 wt.%, 0.3 wt.%, 0.5 wt.%, 0.7 wt.% and 0.9 wt.%
Normal air	As foam booster	0.3 L/min, density of 1.293 kg/m^3

3.0 RESULTS AND DISCUSSION

3.1 Hydrophobicity Test

The contact angle obtained from ImageJ software is 14.6°. This implies that the RHA-NP is hydrophilic in nature. Figure 5 shows the screenshot from ImageJ software analyzing the contact angle.
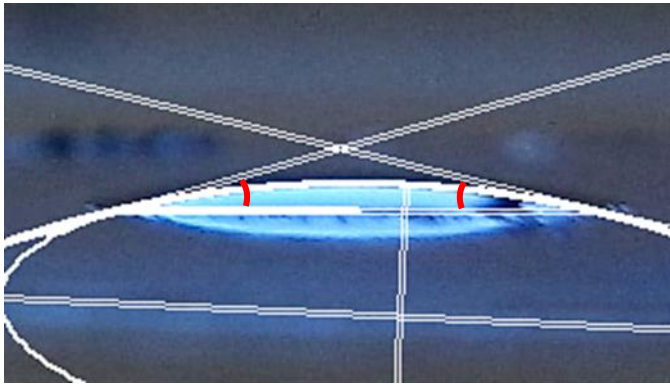
Figure 5 Screenshot of ImageJ software analyzing the contact angle of RHA-NP

Figure 6 Observations of foaminess of surfactant foams added with RHA-NP

3.2 Dispersion Stability Test

The results were tabulated in Table 4. SDS, SDBS and Triton X-100 have PDI_{avg} of lower than 0.200, which implies a good dispersing stability among the particles in the solution. Higher value of PDI_{avg} indicates agglomeration. Therefore, that particular surfactant is no longer suitable to be used to disperse RHA-NP. Generally from the results, higher PDI_{avg} also gives higher d_{avg} reading. As such can be seen in AOS, it gives the highest values of both PDI_{avg} and d_{avg}, thus, it is considered ineffective in dispersing RHA-NP as compared to the other three surfactants.

Table 4 Results of dispersion stability test

Type	Surfactant	PDI_{avg}	d_{avg} (nm)
Anionic	SDS	0.127	162.5
	SDBS	0.132	159.2
	AOS	0.220	184.5
Non-ionic	Triton X-100	0.116	162.8

3.3 Foamability Test

This test was conducted to study the performance of RHA-NP on the foaminess of different surfactants (Figure 6). The higher the foam height, the better is the foaminess. The height of each foam was tabulated (Table 5). Results show that SDS had the best foaminess with the highest foam produced whereas the foaminess of AOS was the lowest. This might imply that the foaminess of SDS is not affected by the addition of the RHA-NP. Furthermore based on the observation, the bubbles foam generated in SDS with RHA-NP were denser and smaller in sizes. Thus, making SDS the best surfactant among the four. Despite the better result from the previous tests, according to Esmaeilzadeh *et al*. (2014), SDS also works well with nanoparticles when injected as part of an EOR process [32].
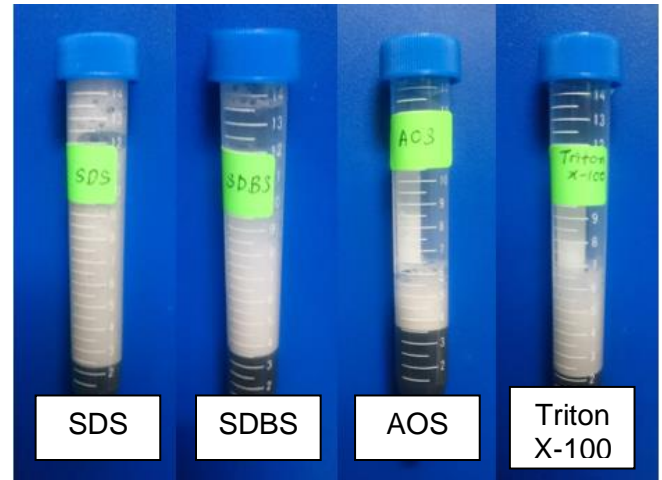
Table 5 Height of the surfactant foams with RHA-NP

Surfactant	Foam height reading (scale division of the centrifuge tube)
SDS	12.5
SDBS	6.5
AOS	2.5
Triton X-100	5.0

Following the foamability test, SDS was chosen to proceed with the foam stability test.
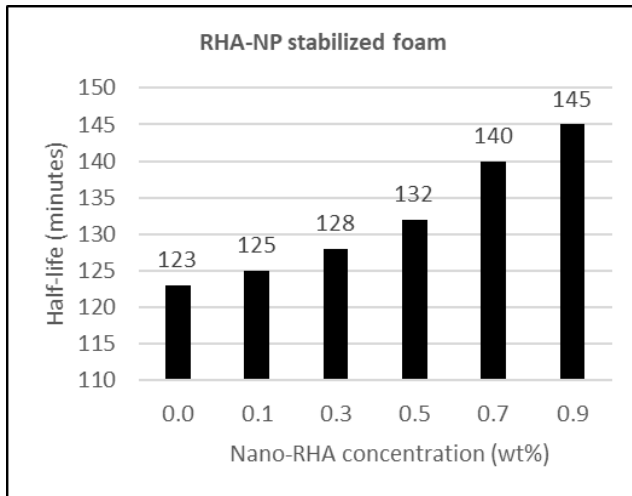
3.4 Foam Stability Test

3.4.1 Effect of RHA-NP Concentration on the Foam Stability Performance

The stability of SDS foam was first tested without the addition of RHA-NP. It acted as the control of the experiment. Then, RHA-NP was added and varied with 5 concentrations from 0.1 wt.% to 0.9 wt.%. RHA-NP were added into 80 mL of DI water accordingly to the weight concentration as shown in Table 6.

Figure 7 shows the trend of the stability performance with the addition of RHA-NP. The increase in RHA-NP concentration leads to the increase in the foam half-life. The highest concentration used, i.e. 0.9 wt.% successfully enhanced the half-life of the original SDS foam by 18%. It is believed that the hydrophilic nanoparticles increase the stability of the foam lamellas by adsorbing themselves on the liquid phase, thus reducing the drainage time which promotes longer half-life [33]. Further studies on varying the concentrations of RHA-NP should be done in order to identify the trend beyond 0.9 wt.% and to find the optimum concentration of RHA-NP in stabilizing SDS foam.

Table 6 The concentration of RHA-NP and their respective weight needed

Concentration (wt.%)	Weight (g)
0.1	0.08
0.3	0.24
0.5	0.40
0.7	0.56
0.9	0.72

Figure 7 Stability performance of SDS foam enhanced by RHA-NP

3.4.2 Comparison between RHA-NP and SiO₂-NP in Foam Stabilizing Performance

The experiment was repeated using SiO_2-NP (without surface modification) with the same concentration used in RHA-NP. The commercial SiO_2-NP gives slightly better foam stability with the increment percentage as shown in Table 7.

Table 7 Comparison of RHA-NP and SiO_2-NP performances

| wt.%	RHA-NP (min)	SiO₂-NP (min)	Increment percentage (%)
0.1	125	128	2.40
0.3	128	130	1.56
0.5	132	134	1.52
0.7	140	142	1.43
0.9	145	154	6.21

With the addition of 0.9 wt.%, SiO_2-NP only gives an increment in the half-life at around 6.21%. Below 0.9 wt.%, the increment is less than 3% for all the concentrations tested. Therefore, it generally shows that RHA-NP is delivering remarkable foam stabilizing ability as compared to commercial SiO_2-NP.

3.4.3 Effect of RHA-NP on Foam Structure

The foams structure and shape distribution were observed and compared for SDS generated foam, SDS with 0.9 wt.% RHA-NP at 60s, 3600s, and 8700s. Figure 8 to Figure 11 show the respective snapshots obtained from the foam analyzer software.

The bubble size distribution histogram was plotted beside the image captured. The bubble size of the foam plays an important role in defining a stable foam. Stable and strong foam bubbles are generally spherical in shapes and appear to be denser. Whereas weak foam bubbles are polygonal in shape and appear thinner. Thin lamellas are thermodynamically unstable. The foam generated with SDS only without additives were comparatively bigger in size compared to that of RHA-NP added. As the foams disintegrated, showing the bubbles size distribution varies from 0-10 000 px. Over time, liquid drainage became severe, causing the lamellas to become thinner and the foam become unstable which eventually collapse.

The smaller the bubbles sizes, the more stable the foams are. In porous media, smaller bubbles will be able to pass through the pore without any division occurring whereas bigger bubbles will undergo bubble division which eventually causes the lamellas to coalesce in the process due to liquid drainage [34]. The conventional sandstones reservoir rocks pore throats size is reported larger than 2 µm [35]. Hence, it is preferable of having bubbles less than 2 µm to minimize bubble division.
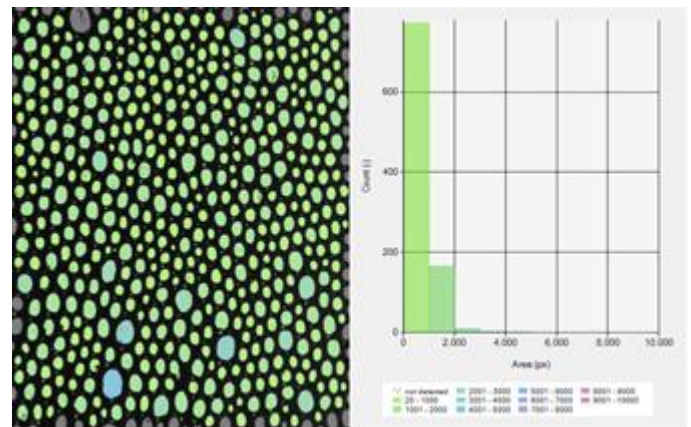
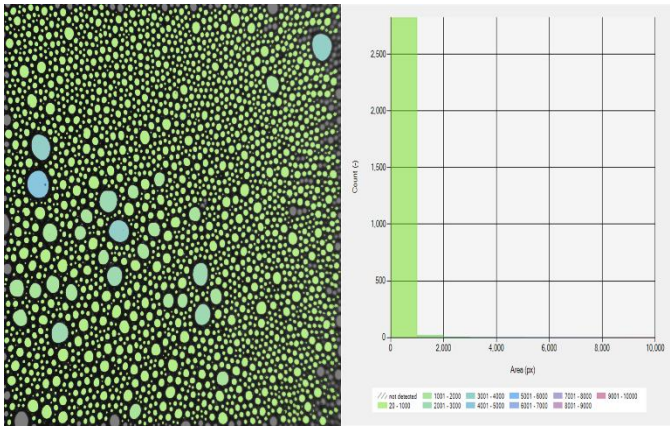**Figure 8** Bubbles structure and size distributions of SDS foam; at 60s

Figure 9 Bubbles structure and size distributions of SDS and 0.9 wt.% RHA-NP foam; at 60s, stable foam with small bubble sizes
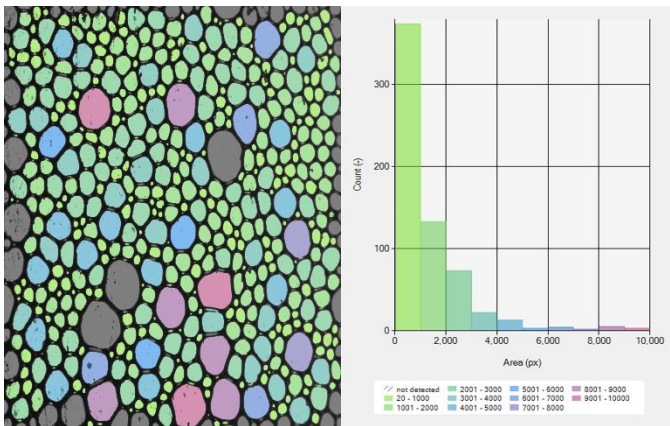

Figure 10 Bubbles texture and size distributions of SDS and 0.9 wt.% RHA-NP foam; at 3600s, liquid drainage occurring, foam started to coalesce
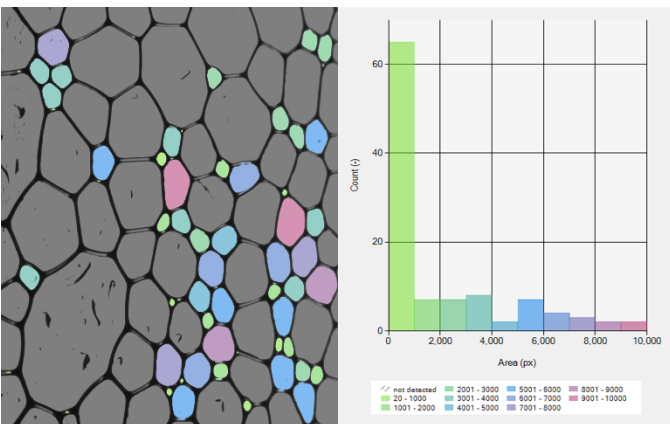

Figure 11 Bubbles texture and size distributions of SDS and 0.9 wt.% RHA-NP foam; at 8700s, fragile foam with severe liquid drainage

3.4.4 Effect of Particle Sizes in Foam Stability Performance

The foam stability was investigated using RHA with original size as to compare with RHA-NP at the same concentration, i.e. 0.9 wt.%.
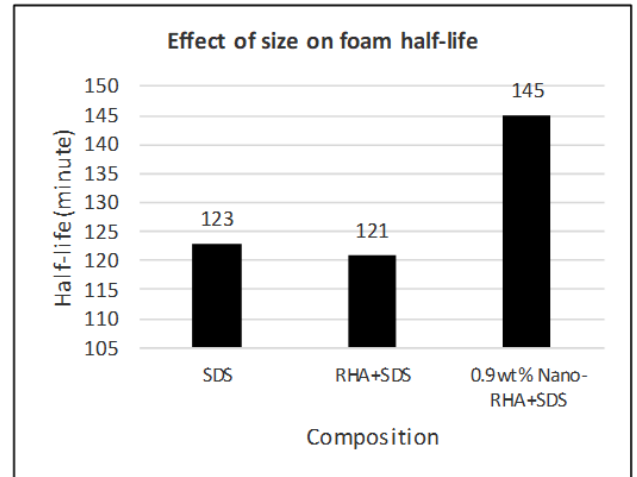

Figure 12 The effect of additives size on the foam stability performance

Figure 12 shows the comparison of foam stability without nano-RHA, with 0.9 wt.% RHA and with 0.9 wt.% nano-RHA. Results show that using 0.9 wt.% of original size RHA slightly decreased the half-life. On the other hand, the stability of the foam was higher with RHA-NP as an additives. The result was expected because according to Hunter *et al.* (2008), the particle size of the additive is one of the key parameters in stabilizing foam [36]. Hydrophilic nanoparticles stabilizes foam by adsorbing into the bubble lamellae and forming a barrier between the gas phases. High adhesion energy between nanoparticles and the lamellae will retard liquid drainage and hence delaying the coalescence of bubbles foam, making the foam more stable over time [33].

3.4.5 Effect of Oil on the Bulk Foam Generation

The results (Figure 13) show that foams stabilized by RHA-NP and SiO_2-NP. Both decreases in their half-life. Bulk foam stability is poor in the presence of oil. Positively, the trend increases with the addition of RHA-NP and it managed to increase the half-life of the SDS foam by 20.7%. On the other hand, SiO_2-NP performed better than RHA-NP by a merely 4.76%. The characteristics of the detrimental effect of oil on foam has been mentioned by Zanganeh *et al.* (2009) and it is very complicated [37]. It is however, the effect of oil on foam generation is unknown [38].
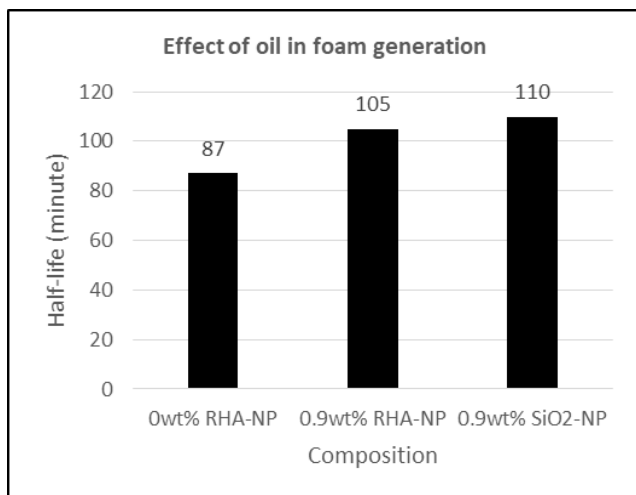
Figure 13 Effect of oil in bulk foam generation

4.0 CONCLUSION

This work presents the idea of utilizing RHA as an additive to enhance the foam stability used in EOR. Despite high purity SiO2-NP can be effectively derived from RH; using RHA without any chemical processes such as acid leaching can save the costs. Besides, using sustainable waste material also meant to prevent pollution of the environment.

In conclusion, this work demonstrates the ability of RHA-NP to enhance the half-life of surfactant air foam (SDS) in both presence and absence of oil even at using minor concentration of 0.9wt%. Besides, the performance of RHA-NP is comparable to that of using commercial hydrophilic SiO2-NP without surface modification. Last but not least, the RHA-NP stabilized foam possesses stable foam texture qualities. Hence, RHA-NP is a potential alternative of foam stabilizing additive.

Acknowledgement

References

[1] Flower, S. 2017. Conventional exploration – Playing Devil's Advocate. Retrieved from https://www.woodmac.com/news/the-edge/conventional-exploration-devils-advocate/.

[2] Floride, A. G. 2013. Meeting Global Demands. *Oil and Gas Financial Journal*. 8-11.

[3] Abu El Ela, Mahmoud *et al*. 2008. Thermal Heavy-oil Recovery Projects Succeeded in Egypt, Syria. *OGJ*. 106: 48.

[4] Abu El Ela, M., Sayyouh, H., and El Tayeb, E. S. 2014. An Integrated Approach for the Application of the Enhanced Oil Recovery Projects. *Journal of Petroleum Science Research*. 3(4): 176.
DOI: doi.org/10.14355/jpsr.2014.0304.03.

[5] Lake, L. W. 1989. *Enhanced Oil Recovery*. Prentice Hall.

[6] Hirasaki, G. J. 1989. Supplement to SPE 19505, The Steam-Foam Process—Review of Steam-Foam Process Mechanisms. Society of Petroleum Engineering.

[7] Zhu, T., Strycker, A., Raible, C. J., and Vineyard, K. 1998. Foams for Mobility Control and Improved Sweep Efficiency in Gas Flooding. *Most*. 277-286.
DOI: doi.org/10.2118/39680-MS.

[8] Tan, X. K. 2017. Nanosilica-Stabilized Supercritical Carbon Dioxide Foam for Enhanced Oil Recovery Application .Master Dissertation. Universiti Teknologi Malaysia, Skudai Johor, Malaysia.

[9] Belhaij A, Mahdy O. A. 2015. Foamability and Foam Stability of Several Surfactants Solutions: The Role of Screening and Flooding. *J Pet Environ Biotechnol*. 6: 227.
DOI: 10.4172/2157-7463.1000227.

[10] Farzaneh, S. A., and Sohrabi, M. 2013. A Review of the Status of Foam Applications in Enhanced Oil Recovery. *EAGE Annual Conference and Exhibition*.

[11] Kaptay, G., and Babcsán, N. 2012. Particle Stabilized Foams. *Foam Engineering: Fundamentals and Applications*. 2000: 121-143.
DOI: doi.org/10.1002/9781119954620.ch7.

[12] Borchardt, J. K., Bright, D. B., Dickson, M. K., and Wellington, S. L. 1988. Surfactants for Carbon Dioxide Foam Flooding. *Surfactant-Based Mobility Control*. American Chemical Society. 373: 163-180–8.
DOI: doi.org/doi:10.1021/bk-1988-0373.ch008.

[13] Yin, G., Grigg, R. B., and Svec, Y. 2009. Oil Recovery and Surfactant Adsorption during CO_2-Foam Flooding. *2009 Offshore Technology Conference*.
DOI: doi.org/10.4043/19787-MS.

[14] Khajehpour, M., Etminan, S. R., Goldman, J., Wassmuth, F., and Technology, A. I. 2016: Nanoparticles as Foam Stabilizer for Steam-foam Process. *SPE EOR Conference at Oil and Gas West Asia*. 14.

[15] B. P. Binks, T. S. Horozov, Angew. Chem. 2005. Aqueous Foams Stabilized Solely by Silica Nanoparticles.
DOI: https://doi.org/10.1002/ange.200462470.

[16] Zhang, T., Espinosa, D. A., Yoon, K. Y., Rahmani, A. R., and Yu, H. 2011. Engineered Nanoparticles as Harsh-Condition Emulsion and Foam Stabilizers and as Novel Sensors. *Offshore Technology Conference*. 1-15.

[17] Handy, R. D., Owen, R., Valsami-Jones, E. 2008. The Ecotoxicology of Nanoparticles and Nanomaterials: Current Status Knowledge Gaps, Challenges, and Future Needs. *Ecotoxicology*. 17: 315-325.

[18] Espinosa, D., Caldelas, F., Johnston, K., Bryant, S., & Huh, C. 2010. Nanoparticle-stabilized Supercritical CO_2 Foams for Potential Mobility Control Applications. SPE 129925, *Proceeding of the SPE Improved Oil Recovery Symposium, Tulsa*.

[19] Worthen, A. J., Bagaria, H. G., Chen, Y., Bryant, S. L., Huh, C., & Johnston, K. P. 2013. Nanoparticle-stabilized Carbon Dioxide-in-Water Foams with Fine Texture. Journal of Colloid and Interface Science. 391: 142-151.

[20] Cui, Z. G., Cui, C. F., Zhu, Y., & Binks, B. P. 2011. Multiple Phase Inversion of Emulsions Stabilized by In Situ Surface Activation of $CaCO_3$ Nanoparticles via Adsorption of Fatty Acids. *Langmuir*. 28(1): 314-320.

[21] Zhang, S., Sun, D., Dong, X., Li, C., & Xu, J. 2008. Aqueous Foams Stabilized with Particles and Non-ionic Surfactants. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 324(1): 1-8.

[22] Cui, Z. G., Cui, Y. Z., Cui, C. F., Chen, Z., & Binks, B. P. 2010: Aqueous Foams Stabilized by In Situ Surface Activation of $CaCO_3$ Nanoparticles via Adsorption of Anionic Surfactant. *Langmuir*. 26(15): 12567-12574.

[23] Binks, B. P., Campbell, S., Mashinchi, S., & Piatko, M. P. 2015. Dispersion Behaviour and Aqueous Foams in Mixtures

of a Vesicle-Foaming Surfactant and Edible Nanoparticles. *Langmuir*. 31(10): 2967-2978.

[24] Singh, R., Gupta, A., Mohanty, K. K., Huh, C., Lee, D., & Cho, H. 2015. Fly Ash Nanoparticle-stabilized CO_2-in-Water Foams for Gas Mobility Control Applications. Society of Petroleum Engineers. DOI: 10.2118/175057-MS.

[25] J. Wong, S. K. 2017. Fly Ash Nanoparticles Enhance Foam Stability Performance in SDS-Stabilized Foam. Undergraduate Dissertation. Universiti Teknologi Malaysia, Skudai Johor, Malaysia.

[26] Pode, R. 2016. Potential Applications of Rice Husk Ash Waste from Rice Husk Biomass Power Plant. *Renewable and Sustainable Energy Reviews*. 53: 1468-1485. DOI:10.1016/j.rser.2015.09.051.

[27] Soltani, N., Bahrami, A., Pech-Canul, M. I., & González, L. A. 2015. Review on the Physicochemical Treatments of Rice Husk for Production of Advanced Materials. *Chemical Engineering Journal*. 264: 899-935.

[28] Thuadaji, N., & Nuntiya, A. 2008. Preparation of Nanosilica Powder from Rice Husk Ash by Precipitation Method. *Chiang Mai Journal of Science*. 35(1): 206-211.

[29] Ogolo, N. A., Olafuyi, O. A., and Onyekonwu, M. O. 2012. Enhanced Oil Recovery Using Nanoparticles. *SPE Saudi Arabia Section Technical Symposium and Exhibition*.

[30] Della, V.P. & Kühn, I & Hotza, Dachamir. 2002. Rice Husk Ash as an Alternate Source for Active Silica Production. *Materials Letters*. 57: 818-821. DOI: 10.1016/S0167-577X(02)00879-0.

[31] Friedmann, F. and Jensen, J. A. 1986. Some Parameters Influencing the Formation and Propagation of Foam in Porous Media. Paper SPE 15087.

[32] Esmaeilzadeh, P., Hosseinpour, N., Bahramian, A., Fakhroueian, Z., Arya, S. 2014. Effect of ZrO2 Nanoparticles on the Interfacial Behavior of Surfactant Solutions at Air–water and N-Heptane–Water Interfaces. *Fluid Phase Equilibria*. 361(0): 289-95.

[33] Yoon, I. H., Yoon, S. B., Jung, C. H. *et al*. 2019. A Highly Efficient Decontamination Foam Stabilized by Well-dispersed Mesoporous Silica Nanoparticles, Colloids and Surfaces A: Physicochemical and Engineering Aspects. 560: 164-170 DOI: https://doi.org/10.1016/j.colsurfa.2018.10.002.

[34] Ransohoff, T., and Radke, C. 1988. Laminar Flow of a Wetting Liquid Along the Corners of a Predominantly Gas-Occupied Noncircular Pore. *Journal of Colloid and Interface Science*. 121(2): 392-401. DOI: doi.org/10.1016/0021-9797(88)90442-0.

[35] Nelson, Philip H. 2009. Pore-throat Sizes in Sandstones, Tight Sandstones, and Shales. *AAPG Bulletin*. 93(3): 329-340.

[36] Hunter, T. N., Pugh, R. J., Franks, G. V. *et al*. 2008: The Role of Particles in Stabilising Foams and Emulsions. *Advances in Colloid and Interface Science*. 137(2): 57-81. DOI: doi.org/10.1016/j.cis.2007.07.007.

[37] Zanganeh, M. N., Kam, S. I., LaForce, T. C., and Rossen, W. R. 2009. The Method of Characteristics Applied to Oil Displacement by Foam. *SPE EUROPEC/EAGE Annual Conference and Exhibition*.

[38] Farajzadeh, R., Andrianov, a., Krastev, R., Hirasaki, G. J., and Rossen, W. R. 2012. Foam-oil Interaction in Porous Media: Implications for Foam Assisted Enhanced Oil Recovery. *Advances in Colloid and Interface Science*. 183-184: 1-13. DOI: doi.org/10.1016/j.cis.2012.07.002.