Effect of the presence of a dispersed phase (solid particles, gas bubbles) on the viscosity of slag

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2009
Abstract

The viscosities of a set of silicone oils containing different size ranges of charcoal or paraffin particles as well as the viscosities of silicone oil foams were measured at room temperature in order to determine the effect of dispersed phase on the viscosity of a liquid and its effect on foaming ability. The effective viscosity of the samples increased with volume fraction of the second phase. The foaming ability was improved by the presence of the particles. The improved foaming effect was for the most part not a result of the increased viscosity. No connection between the particle size and the effective viscosity could be determined. On the other hand particle morphology and the particle size distribution had effect on the effective viscosity. The viscosity data were compared with a number of existing equations for the estimation of effective viscosity. Einstein-Roscoe equation is suitable for two-phase mixtures containing globular particles with narrow particle size distribution and low interfacial tension. New mathematical models are required for effective viscosity prediction, where the suspending phase viscosity, effect of the interfacial tension, as well as the particle morphology should be taken in consideration.

Keywords: Mathematical modelling, Physical modelling, Slag viscosity, Slag foaming.
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I. Introduction

The main factors that influence the viscosity of the foam are the size of bubbles in the foam, the volume fraction of the gas phase and the interfacial tension between gas and liquid. The viscosity of foam increases with volume fraction of gas phase if the foam is stable and the bubbles are small and well dispersed. In this case high volume fractions foams shall be considered as structured materials, since the rheology properties and structure are closely coupled. Solid-like behavior was earlier reported for foams containing above 70 volume percent of a gas phase. Those foams appear to have a yield stress. At low stresses the foam moves as a solid body. At higher stresses the foam starts to shear.\cite{1} In metallurgical processes the foaming properties of slag are of industrial importance. Slag foam provides better heat transfer from arc to the melt, and also acts as a thermal insulator between the hot bath and the surroundings, thus reducing the electrical power required to maintain the high operating temperature and limiting electrode consumption. In addition, slag foam prevents the melt from oxidizing and enables control of its composition. The surface area of the metal slag interface is increased and therefore the reducing conditions of metal are improved.\cite{2} On the other hand excessive foaming may cause the vessel to overflow, which can be a limiting factor for the productivity of smelting-reduction technologies. Thus it is important to have a toll for regulation of the foaming properties of slag.\cite{3} There are two main mechanisms of slag foaming: when foam is generated by injected gas, the height of the slag foaming can be regulated, and when gas is produced by chemical reactions and in this case the height is difficult to control. Formation and stability of foams depend upon a variety of factors, among others, the base viscosity of the fluid and presence of solid particles in the fluid, playing an important role. Higher viscosity is supposed to stabilize the foam since it hinders the liquid that surrounds the bubble from draining. On the other hand, bubble formation becomes impossible if the viscosity of the liquid is too high. It is also believed that a low surface tension is favorable for slag foaming ability, since a high surface tension value increases the energy requirement for the formation of a bubble.\cite{4} Presence of second-phase particles for example CaO or CaO\textsubscript{2}SiO\textsubscript{2} can have a large effect on foam stability because they increase the bulk viscosity of the slag. The effect of interfacial tension between solid particles and the melt may affect the foaming properties of the slag. Solid inclusions are often present in slag due to precipitation, entrapment or external addition of for example coke and iron ore. Addition of coke particles due to its low wettability for slag may break up the foam mechanically or it may speed up the breakdown of the foam by building new CO-bubbles.
Addition of iron ore into slag decreases the temperature and thus temporarily increases the viscosity. High viscosity facilitates the foaming ability. The result is strong foaming of the slag since many small independent bubbles are formed. As the temperature increases again the drop in the viscosity takes place and then smaller bubbles fuse into larger ones. Large bubbles stream easily to the top; in this case no foam is formed.[5,6]

There are several existing expressions that are derived for prediction of viscosity of two-phase mixtures. The effective viscosity of a suspension, $\eta_r$, according to Einstein, is described by an equation:

$$\eta_r = 1 + 2.5f$$

where $\eta_r = \eta / \eta_0$ is referred to as the relative viscosity of the continuous fluid, and $f$ is the volume fraction of the suspended hard spherical particles. Einstein’s model is valid for low concentrations of solid spherical particles, since the influence of particle interaction is not considered. For suspensions with $f < 0.05$, the Einstein prediction has been confirmed in numerous experimental observations. For more concentrated suspensions, experiments show a substantially more rapid increase in $\eta(f)$ with increasing $f$, than that predicted by Einstein.[7]

One other relationship describing the viscosity of liquids containing solid (spherical) particles is the Einstein-Roscoe type equation:

$$\eta = \eta_0 (1 - \alpha f)^n$$

where $\eta$ is the viscosity of the mixture containing solid particles and $\eta_0$ is viscosity of solid-free liquid; $f$ is the volume fraction of solid particles added; $\alpha$ and $n$ are constants. The reciprocal of $\alpha$ represents the maximum amount of solid that the liquid phase can accommodate as viscosity attempting to reaches the infinity. For spherical mono-sized particles $\alpha$ is set to 1.35 and $n$ to 2.5 according to Roscoe.[8]

The effects of volume fraction and maximum volume fraction on viscosity are described using the Krieger-Dougherty equation:

$$\eta_r = (1 - f / f_m)^{[\eta]/f_m}$$

where $\eta_r$ is the effective suspension viscosity, $[\eta]$ and $f_m$ are the intrinsic viscosity and maximum packing fraction of solids. Theoretically, $[\eta]$ should be 2.5 for rigid spheres and $f_m$ should be about 0.62 if the spheres are of uniform diameter. The Krieger-Dougherty (1959) relationship is based on assumption that an equilibrium exists between individual spherical particles and dumbbells that continuously form and dissociate. This correlation indicates an
increase in viscosity with increasing volume fraction. As the volume fraction of solids in the system goes up, the particles become closely packed together; it becomes more difficult for them to move freely, particle-particle interactions increase, and resistance to flow (viscosity) rises. As the volume fraction nears maximum for the sample, viscosity rises very abruptly. At higher volume fractions, particle size distribution influences particle packing. A polydisperse population with a broad size distribution packs closely than a monodisperse sample. The effects on viscosity can be explained with reference to Krieger-Dougherty equation. For a monodisperse sample the maximum volume fraction is around 0.62. With a polydisperse sample smaller particles can fill gaps between larger ones and the maximum volume fraction is greater – around 0.72. Particle size distribution can be a valuable tool for manipulating the viscosity of a system that contains a fixed volume fraction of solid particles. A minimum viscosity is achieved when particles of two different sizes are present at a certain concentration. The resulting viscosity is lower than that achieved using a monodisperse sample. If the requirement is a higher solid loading but with the same viscosity then this can be achieved by broadening the particle size distribution. Conversely viscosity can be increased by using particles with narrowed size distribution.\(^9,10\)

The spherical cell approach is an approximate method to describe a macroscopically uniform and isotropic media. SC approach can be applied for studying the role of interfacial forces in rheological behavior of colloid systems. The method is based on the assumption that, at the microscopic level, a representative volume for the medium is a sphere (SC) which, in its center, contains one of the constituting kinetic units (atom, molecule, dispersed particle, etc.). This assumption enables to take into account complex multi-particle interactions between the species composing the medium, such as dielectric permittivity, conductivity, hydrodynamic permeability, etc. The influence of the interfacial electrical forces on the effective viscosity of concentrated suspensions may also be considered. Happel developed a mathematical model for prediction of the viscosity of suspensions, using spherical cell approach:

\[
\eta_r = 1 + f \left[ 22 f^{7/3} + 55 - 42 f^{2/3} \right] / \left[ 10(1 - f^{10/3}) - 25(1 - f^{4/3}) \right] h
\]

where \(\eta_r\) is relative viscosity of a suspension and \(f\) is a volume fraction of the suspended solid spheres. Consider a suspension that contains spherical solid particles, see Figure 1, where \(a\) is the particle radius and \(b\) is the radius of SC. The outer fluid shell \(b\) encloses an amount of fluid in proportion to the fluid to solid volume of the suspension. In the absence of suspended particles, the fluid flow field is assumed to consist of a simple shearing motion with a
constant velocity gradient. The flow disturbance caused by each solid sphere is assumed to be limited to a frictionless fluid cover surrounding the sphere. For dilute suspensions it is also assumed that: the inertial effect may be neglected; and the fluid adheres perfectly to the suspended rigid spheres.\cite{7}

![Figure 1- Happel’s spherical cell (SC), where \( a \) is the particle radius and \( b \) is the radius of SC.](image)

Thomas D. G. developed an empirical formula for estimation of relative viscosity of colloids:

\[
\eta_r = 1 + 2.5f + 10.05f^2 + A \exp(Bf)
\]

Where, \( \eta_r \) is relative viscosity of the suspension; \( f \) is volume fraction of the suspended solid particles; \( A \) and \( B \) are adjustable coefficients that were found to be 0.00273 and 16.6, respectively.\cite{11}

The aim of this work is to determine the effect of dispersed phase on the viscosity of a liquid and its effect on foaming ability; to find out if the present models can be used for prediction of the viscosity values of two phase mixtures; to investigate the influence of particle size as well as amount of the suspended phase and effect of interfacial tension on the effective viscosity.
II. Experimental

Setup

A digital Brookfield LVDVII +Pro Viscometer was used in this work. Viscometer measures the torque required to rotate the spindle in a fluid. For a given viscosity, the viscous drag, or resistance to flow, is proportional to the spindle’s speed of rotation and is related to the spindle’s size and shape (geometry). The drag will increase as the spindle size and/or rotational speed increase. The experimental apparatus for the determination of viscosity is shown in Figure 2.\(^\text{[12]}\)

![Figure 2-The viscometer apparatus.](image)

Materials

Silicone oils of two different viscosities were used as the bulk phase. Silicone oils used for this work were 100cP and 200cP respectively, (supplied by Dow Corning Corporation, USA). Quality controlled hardwood charcoal (of broadleaves) produced by GRYF SKAND, Forest Stewardship Council, was used for charcoal particles preparation. Pieces of charcoal were first smashed manually into powder using a hammer. The powder was sieved using a series of sieves to obtain fine powders with different ranges of particle sizes. The charcoal density was determined to be 0.33 g/cm\(^3\). Paraffin powder of density 0.93 g/cm\(^3\) was prepared of paraffin produced by Joel Svenssons Vaxfabrik, Sweden. Very fine stripes were first prepared of paraffin pieces using conventional kitchen grater. Then the strips were carefully grinded and
sieved. Mass percent of particles in the mixture are given in the Table 1. Size rages of the particles used, given in µm, are shown in the Table 2.

Table 1- Size rages of the particles.

<table>
<thead>
<tr>
<th>Particles size [µm]</th>
<th>150&lt;</th>
<th>150-250</th>
<th>250-335</th>
<th>335-425</th>
</tr>
</thead>
</table>

Table 2-Mass percent of particles.

<table>
<thead>
<tr>
<th>Mass percent of particles</th>
<th>0.05</th>
<th>0.08</th>
<th>0.17</th>
<th>0.30</th>
<th>0.67</th>
<th>1.33</th>
<th>3.33</th>
<th>10.00</th>
</tr>
</thead>
</table>

Procedure
Viscosity measurements of the silicone oil/powder mixtures were conducted within a rotational speed interval of 20 to 140 RPM. Average values of sample viscosities were then extracted from the regions with constant viscosity values (40 to 80RPM). The results were then plotted as a function of mass percent of the particles added. All viscosity measurements were conducted using the spindle guardleg and a standard stainless steel disc type LV#2 spindle. A 250ml Bomex glass beaker (12cm in height and 6cm in diameter) was used as a sample container. The readings of viscosity values were taken within 5 minute after the rotation had started to avoid effects of sedimentation or floatation of the particles.

160g of silicone oil of certain viscosity was taken for each measurement (approximately 175 ml). In first step the viscosity of pure silicone oil was measured for different rotation speed. Then the same procedure was repeated each time pre-weighted amounts of powder were added in. The two-phase mixture was stirred manually for at list one minute using a glass rod before every new measurement.

The temperature of the mixture was held constant at 298 K using a temperature bath with circulating warm water (Neslab gp-200, Chemical Instruments AB, Sweden). The temperature of the sample was controlled by immersing the thermometer into the mixture after every new portion of powder was added in. A thermometer used was of stainless steel. The temperature values were read after the sample has reached the 298K and the thermal steady state was attained. Silicone oil and the powders were weighted with ±0.01g accuracy using a Mettler PJ3000 balance, (Mettler-Toledo AB, Switzerland). Before every experiment, the sample container, as well as a thermocouple and the spindle were cleaned carefully and the viscometer was auto zeroed.
Foam viscosity measurements
Foam viscosity measurements were conducted at room temperature. The foam viscosities of three different silicon oils with initial viscosities of 86, 132 and 183 cP were measured. Rotation speed of 100 RPM was applied. The torque values exceeded 30 percent. The records were made using Rheocalc software. During each measurement the foam viscosity values were taking every second within 1 minute interval and plotted as a function of time. Then the average values were extracted from the stable regions of the curves and plotted as a function of flow rate.

Microscopy studies
Microscopy studies of charcoal and paraffin particles were conducted using LEICA DMRM optical microscope, (Leica Microsystems). The powder samples were fixed in epoxy between microscope slides and coverslips. The pictures (magnification 2.5x10) were taken with an incorporated digital video camera (Sony hyper HAD) in order to investigate the particle morphology and particle size distribution.

Interfacial tension test
A simple wetting test was conducted at room temperature for estimation of interfacial tension: the surfaces of paraffin sample respectively charcoal sample were polished and droplets of pure silicone oil with viscosity value of 200 cP were applied on the polished surface. Then the pictures of the samples were taken in order to determine the contact angle.
III. Results and discussion

Results from the interfacial tension test demonstrate that both charcoal and paraffin samples have good wetting with silicone oil, see Figure 3 and Figure 4. However, for both samples, the contact angle was difficult to determine since it was very low. Very low contact angle indicates that there is low interface energy between solid and liquid phases and the wetting is complete. The charcoal sample absorbed some oil, remaining oil stains were observed on the charcoal sample surface after the silicon oil was removed. The interfacial energy between molten slag and oxide particles is in general very low and the wetting is good. Consequently the results in this work may be used for slag containing solid oxide particles.\textsuperscript{[13]}

Figure 3- Interfacial tension test, paraffin sample

Figure 4- Interfacial tension test, charcoal sample.
Viscosity of two-phase mixtures

The measured viscosities were generally found to be independent of the torque when silicone oil of 200cP was used as a bulk liquid. Contribution of turbulent viscosity in a fluid of higher viscosity is lower since the flow is less turbulent and particles are in addition hindered to rotate. The independence of the values of the rotation speed indicates that in this case the two-phase mixture could be considered as a Newtonian liquid. Figure 5 shows viscosity of a mixture containing large (335–425µm) charcoal particles suspended in silicone oil of viscosity of 200cP as a function of rotation speed.

![Figure 5- Viscosity of a mixture containing large (335-425µm) charcoal particles suspended in silicone oil with viscosity of 200cP as a function of rotation speed.](image)

Viscosity of mixtures containing different amounts of large (335-425µm) charcoal particles suspended in silicone oil of viscosity of 100cP showed in contrast changes with the torque. Figure 6 shows the viscosity dependence of the mixture containing large (335-425µm) charcoal particles on the rotation speed. At low torque the viscosity remains constant, but above 80 RPM increases linearly with rotation speed.

Measured viscosities of 100cP silicone oil/paraffin particles mixtures also shown changes with rotation speed. Figure 7 shows viscosity of a two-phase mixture with viscosity of silicone oil of 100cP, containing small (<150 µm) paraffin particles as a function of rotation speed. It can be seen that the viscosities of the mixtures increase as a function of rotation speed. The dependence of the viscosity on the rotation rate indicates that the two-phase mixtures turn from Newtonian fluids into non-Newtonian.
Figure 6 - Viscosity of a mixture containing large (335-425µm) charcoal particles suspended in silicone oil with bulk viscosity of 100cP as a function of rotation speed.

Increase of effective viscosity at higher rotation speeds is due to increase of the turbulent viscosity, which is not a material property, but a property of a flow itself. Thus, the only regions on the curves that represent constant viscosity as a function of rotation speed were selected for analysis. Sedimentation or floatation of the particles could affect the measurements. The density of charcoal is much lower than that of silicone oil and thus the particles can be expected to float. However, the charcoal particles tended to sediment, and large particles appeared to sediment faster than smaller ones. Absorption of oil could increase the density of the charcoal particles and make them sink. The charcoal particle sediment build
up high viscosity slurry on the bottom of the breaker. Paraffin particles in contrast were observed to float. Flotation of paraffin particles can be explained by the fact that paraffin has lower density compared to silicone oil. The sedimentation or flotation, as was observed in the experiment, could not be stopped by the high speed rotation of a spindle (above 100 RPM), thus the readings of viscosity values were taken within 5 minute after the rotation had started. The measurements could also be affected by entrapment of microscopic gas bubbles into the mixture. The gas bubbles may be difficult to remove due to presence of the particles. The density of a charcoal was determined to 0.33 g/cm³ by immersing a bit of charcoal into water. However the measured density may differ somewhat from the density of the charcoal powder since many of the pores are destroyed during the powder preparation.

**Viscosity of a silicone oil and paraffin particles mixture**

Figures 8 and Figure 9 show viscosities of 100cP respectively 200cP silicone oil / paraffin particles mixtures as a function of mass percent paraffin particles added. The viscosities of the mixtures increase nearly linearly with addition of paraffin particles. Particle size does not apparently influence the viscosity of the mixture in the case of paraffin particles.

![Figure 8-Viscosities of 100cP silicone oil and paraffin particles mixture as a function of mass percent particles added.](image-url)
Viscosity of 200cP silicone oil and paraffin particles mixture as a function of mass percent particles added.

**Viscosity of a silicone oil and charcoal particles mixture**

Figure 10 and Figure 11 show viscosities of 100cP respectively 200cP silicone oil/charcoal particles mixtures as a function of mass percent charcoal particles added. In both cases the viscosities increase with amount of charcoal particles.

Figure 10-Viscosity of 100cP silicone oil/charcoal particles mixture as a function of mass percent charcoal particles added.
In the Figure 10, where silicone oil of viscosity 100cP was used as a bulk phase, medium sized of 150-250µm and 250-350µm particles seems to increase the viscosity values in larger extend than small <150µm, and large 350-450µm particles. Similar trend was observed when the silicone oil of 200cP used as a bulk, see Figure 11.

Small amounts of paraffin powder below 0.21 mass percent did not increase the viscosity of the mixture, in some cases the measured viscosity values appeared to decrease, up to 2 percent, which can be explained by fact, that in contact with the spindle the particles may start to rotate instead of following the bulk flow. The same trend was found for the charcoal particles.

Figure 12 shows relative viscosity of 100cP silicone oil/paraffin particles mixture as a function of volume concentration particles added. Einstein-Roscoe type equation shows good fitting with the measured data up to 10 volume percent. Einstein type equation is in good agreement with measured values up to 2 volume percent. Thomas type equation is in good agreement up to 3 volume percent. Happel, on the other hand, significantly exceed the experimental values.
Figure 12 shows relative viscosity of 100cP silicone oil/paraffin particles mixture as a function of volume concentration particles added. Krieger-Dougherty, Thomas as well as Einstein type equations show good fitting with the measured data up to 3 volume percent, but predict lower values at higher volume fractions. Einstein-Roscoe type equation shows best fitting. Happel type equation exceeds the measured values.

Figure 13 shows relative viscosity of 200cP silicone oil/paraffin particles mixture as a function of volume concentration particles added. Krieger-Dougherty, Thomas as well as Einstein type equations show good fitting with the measured data up to 3 volume percent, but predict lower values at higher volume fractions. Einstein-Roscoe type equation shows best fitting. Happel type equation exceeds the measured values.

Figure 13 shows relative viscosities of 200cP silicone oil/paraffin particles mixture as a function of volume concentration particles added.
Einstein-Roscoe equation show quite good fitting for the silicone oil in the rage of 100cP and 200cP using paraffin particles as solid phase. 

Figure 14 shows relative viscosity of 100cP silicone oil/charcoal particles mixture as a function of volume percent charcoal particles added. Einstein-Roscoe and Happel type equations exceed the measured results for 100 cP silicone oil based mixtures. Einstein type equation gives a lower limit for measured values at 15 volume percent. Thomas and Krieger-Dougherty type equations show best fitting to measured values. 

Figure 15- presents the relative viscosity of 200cP silicone oil/charcoal particles mixture as a function of volume percent charcoal particles added. Einstein-Roscoe and Thomas type equations show best fitting for small and large particles. Krieger-Dougherty and Einstein type equations show best fitting to measured values up to 5 volume percent. Happel and Thomas type equations give upper and lower limits for measured values respectively. 

Krieger-Dougherty type equation gives god fitting in case of charcoal particles suspended in silicone oil of 100cP, but fail to predict correct values, if silicone oil of 200 cP is used for sample preparation. Einstein-Roscoe predicts well the measured values with suspension of silicone oil of 200cP as a base fluid.
Figure 15- Relative viscosity of 200cP silicone oil/charcoal particles mixture as a function of volume percent charcoal particles added. Einstein-Roscoe and Thomas type equation show best fitting.

There is no universal expression that would fit in both cases thus a new relationship is needed to describe the effective viscosity of a two-phase mixture where the viscosity of the base fluid is considered. It was concluded in earlier studies that viscosity of a suspension at a given concentration was independent of the viscosity of the suspending liquid.\cite{14} Results in this work, in contrast, indicate that there is a certain dependence of the viscosity of a mixture of the suspending liquid on the effective viscosity. Compare Figures 14 and 15. When small amounts of charcoal particles are added into fluid there are no significant particle-particle interaction, and thus the measured viscosities are either dependent on particle size or particle size distribution. At elevated particle loads influence of particle size distribution and particle morphology on the viscosity can be observed in case of silicone oil / charcoal particles mixtures.

**Results from foam viscosity measurements**

The foam viscosities of three different silicon oils with initial viscosities of 86, 132 and 183cP were measured. The size of the bubbles increased as the flow rate increased and volume fraction of the gas phase seemed to be reduced. At higher flow rates, about 20% smaller bubbles coerced into bigger ones and turbulent bubble flow was observed. Foam videos and pictures from previous work conducted by Wu Liushun\cite{15} were analyzed in order to determine the average bubble size as a function of flow rate and initial viscosity of the oil. However the sizes of foam bubbles as well as the volume fracture of the gas phase were difficult to quantify. The bubble size nevertheless was observed to increase with flow rate.
Figure 16 shows effective viscosity values of silicone oil foams as a function of flow rate. At low flow rates the effective viscosity decreases as a function of flow rate and stagnates at higher flow rates above 15%. The decrease of the foam viscosities at higher flow rates is due to the decreased volume fraction of the gas phase.

The viscosity of each of the foams exceeded the initial sample viscosity. Figure 17 shows relative effective viscosity of silicone oil foams as a function of flow rate. At low flow rates the effective viscosity decreases as a function of flow rate and stagnates to a constant value at higher flow rates above 20%. It can be seen that the relative viscosity of the foams prepared of silicone oils is dependent on the initial viscosity of a fluid and increases with decreased initial viscosities. The foam viscosities of silicone oils with initial viscosities of 183cP 132cP and 86cP are increased by 15%, by 20% for and 40% respectively. This may be due to contribution of turbulent viscosity. The contribution of turbulent viscosity is probably higher in the foams with low viscosity base liquids.
Figure 18 shows normalized foam height as a function of superficial velocity. Experimental data for a foam prepared of silicon oil with initial viscosity of 200cP containing 10 mass percent paraffin particles and resulting bulk viscosity of a mixture of approximately 280cP significantly exceed pre-calculated values as well as measured values for the foam prepared of pure silicone oil of similar viscosity.

![Figure 18](image)

Figure 18 – Normalized foam height as a function of superficial velocity (cm/s).

It was earlier concluded that the foam index increases due to the presence of second-phase particles (CaO or CaOSiO$_2$), because the particles increase the bulk viscosity of the slag. It is obvious that the viscosity of a liquid increases with the amount of particles. Higher viscosity is believed to facilitate foaming stability. Addition of 10 mass percent of paraffin particles into silicone oil of 200cP increases the viscosity of a two-phase mixture to 280cP. The resulting foam height is however much higher than the experimental data values for a foam of pure silicone oil of the same (280cP) viscosity. So the effect of particles on foaming ability is mainly not due to increase of viscosity.

**Results from microscopic study of the particles**

Despite similarities in interfacial energies, the viscosity measurement results conducted using paraffin particles cannot be directly compared with those using charcoal particles, since the particle size, the geometry, as well as the particle size distributions differ a lot. Shape of the paraffin particles seemed to be nearly spherical or polyhedral with smooth corners. Figure 19 and 20 show paraffin particles, (semi transparent) of 335-425 and less than 150 µm in diameter respectively. The black disks in the pictures are air bubbles entrapped into epoxy during the preparation of the samples.
Numerous charcoal particles obtained using series of sieves with size ranges above 150µm had a needle like shape with a length distribution of 1 to 3mm. A needle like particle with a length of 3mm and approximately 20 µm in diameter obtained using series of sieves with size ranges of 335-425µm can be seen in Figure 21. Figure 22 shows normal population of charcoal particles obtained using the same series of sieves. Charcoal particles with a length of approximately 0.5-1.5 mm can be observed.
Figure 21 – Large charcoal particles obtained using series of sieves with size ranges of 335-425µm. Needle like particle with a length of up to 3mm can be seen.

Figure 22 – Normal population of charcoal particles obtained using series of sieves with size ranges of 335-425µm. Needle like particles with a length of approximately 0.5-1.5 mm can be observed.

Figure 23 shows charcoal particles of a size range of 150-250µm. Sharp edges of the charcoal particles could possibly lead to bubble rupture if added to the foam. Figure 24 shows small charcoal particles, less than 150µm in diameter. It can be seen that the particle population is polydisperse and that agglomeration of particles, possibly due to large surface energy, may occur. It was concluded in earlier works that viscosity of a suspension is dependent upon the size distribution of the spheres, which is believed to affect the packing grade of the particles at higher volume fractions.\textsuperscript{9,10} According to Krieger-Dougherty formula: increased packing grade will decrease the viscosity of a suspension at the fixed volume fraction of particles. It is emphasized that the equation were derived for suspensions containing rigid solid spheres.
Packing grade is also particle shape dependant. In reality it is very difficult to predict the packing grade for particles of random shape. Results in this work show that small particles give lower viscosity to the two phase mixture; this can be explained by the fact that the particle population is polydisperse and the packing grade is higher than for the medium sized particles. This assumption however is not able to explain why similar viscosity values are achieved when large needle-like particles are involved. Measured viscosity values indicate that particle size does not influence the effective viscosity of two phase mixtures if surface tension between fluid and solid particles is low, charcoal particles of the medium size range (150-250 and 250-335µm), shows almost the same values. Measured values of mixtures containing paraffin particles were not ether size dependent. There is nevertheless a certain effect of the particle shape and particle size distribution on the effective viscosity of the two-phase mixture.
H. Xie et al. in his work conducted on nanofluids concluded that the agglomeration of the nanoparticles in suspensions lead to increased viscosity of the fluid-nanoparticle mixtures. The effective viscosity of the nanoparticle suspension was also found to be much larger than the corresponding value predicted by the theory. The experimental results showed that the base fluid plays a dominant role on the viscosity of a nanofluid when the volume fraction is low. When the concentration becomes higher, the interaction between the base fluid and the solid phase would have larger effect on the viscosity of the nanofluid. Particles are well dispersed when repulsive forces between the nanoparticles are very strong. Decreased repulsion among nanoparticles would lead to their coagulation. Thus the viscosity increases for a nanofluid. \cite{14} Sweeny and Geckler investigated the properties of suspensions of small glass spheres. It was found that viscosity increased with an increase in particle diameter with the aqueous solution employed, but was independent of particle diameter with a nonaqueous fluid. \cite{16} That can be a result of influence of surface tension between solid and liquid phases. Wei Liu et al \cite{17} investigated the effect of the surfactant on the effective viscosities of silicone oil/water emulsions in the work Effect of Interfacial Energy on the Viscosities of Two-Phase Mixtures -A Physical Modeling Approach. It was found that interfacial energy would play an important role in the viscous flow of the two-liquid mixture. The strong effect of the surfactant on the effective viscosities illustrates that the interfacial energy plays an essential role in the effective viscosities of two-phase mixtures. Further investigations are required to determine the influence of the presence of particles on two-phase mixtures with different ranges of interfacial tension.
IV. Conclusions

The viscosities of a set of silicone oils with addition of charcoal or paraffin particles of different size ranges as well as the viscosities of the silicone oil foams were measured at room temperature in order to determine the effect of dispersed phase on the viscosity of a liquid and its effect on foaming ability. The experimental results show that the effective viscosity increases with volume fraction of the second phase in the two-phase mixture. However the effect of particles on foaming ability was mainly found to not be a result of increased viscosity. Particle morphology as well as particle size distribution have shown a certain influence on the effective viscosity. No connection between the particle size and the effective viscosity could be found, which could be due to low interfacial energy between liquid and solid phase. The viscosity data of two-phase mixtures were compared with a number of existing expressions for prediction of the effective viscosity. Einstein-Roscoe type equation can be applied for two-phase mixtures up to 10 volume percent for spherical particles with narrow particle size distribution, if interfacial tension is low. For low concentrations of solid particles any of the chosen models seem to work properly. For more concentrated two-phase mixtures there is a need of new mathematical models for prediction of viscosity, where the suspending phase viscosity, effect of the interfacial tension, as well as the particle morphology should be considered.
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