CHAPTER VIII
CONCLUSIONS AND RECOMMENDATIONS

In this study, poly(3-thiophenacetic acid), PTAA was synthesized via an oxidative polymerization and doped with perchloric acid to control its conductivity. The suspension containing perchloric acid-doped poly(3-thiopheneacetic acid) as dispersed particles and silicone oil as medium was then prepared. The ER characteristics of PTAA/silicone oil suspensions were further investigated in both oscillatory and steady shear using rheometer which equipped to a high-voltage generator. The effects of electric field strength, particle concentration, particle conductivity, operating temperature, nonionic surfactant were examined.

8.1 ER Properties of Polythiophene Suspension under the Oscillatory Shear

When the electric field is applied, the PTAA/silicone oil suspension exhibits viscoelastic behavior and the ER response is enhanced with increasing electric field strength. Experimental results show that the dynamic moduli G' amd G" of the suspension increase dramatically by ten orders of magnitude as the electric field strength is increased up to 2 kV/mm. Viscoelastic behavior of this suspension under an applied electric field arises from the formation of agglomerates induced by the electric polarization within particles. The ER response is enhanced by increasing the electric field strength, the particle concentration, and the particle conductivity. The effects of particle concentration and conductivity become apparent at intermediate electric field strength (~ 100 V/mm). Upon the turning electric field on and off subsequently, the suspension shows instantaneously response. On applying the electric field, G' immediately increases and rapidly reaches a steady-state value in which the induction time is independent of particle concentration or conductivity. After the electric field is released, the sample recovers but not completely and the recovery time is longer at lower particle concentration and lower particle conductivity. Moreover, the PTAA suspension exhibits fluid-like to solid-like behavior transition as the field strength is increased. Furthermore, the frequency-dependent moduli at different electric field strengths and conductivities, when scaled according to the model of Parathasarathy and Klingenberg approximately collapse into single functions of the dimensionless frequency, indicating a moderate success of the model of Parthasarathy and Klingenberg.

8.2 ER Properties of Polythiophene Suspension under the Steady Shear

From the steady shear experiment, the yield stress values are measured. The experimental results show that the PTAA/silicone oil suspension shows the typical ER response of Bingham flow behavior upon the application of electric field. The yield stress increases with electric field strength, E, and particle volume fraction, ϕ, according to a scaling law of the form, $\tau_y \propto E^{\alpha}\phi^{\gamma}$. The scaling exponent α approaches the value of 2, predicted by the polarization model, as the particle volume fraction decreases and when the doping level of the particles decreases. Moreover, the linear relationship between the yield stress and the volume fraction holds at low electric field strength but deviation from linearity occurs at high electric field strength. In addition, the yield stress under electric field initially increases with temperature up to 25 °C, presumably due to enhancement of particle conductivity, and then levels off. The effect of nonionic surfactant addition is evident at relatively weak electric field strength. On applying and subsequently releasing the electric field, respectively, the steady state viscosity and the complex viscosity each instantaneously increase and then return to their baseline values, i.e., complete recovery. Morphology of PTAA/silicone oil suspension under quiescent conditions is further observed using optical microscope. The micrographs show that the particles are randomly distributed at zero field, whereas on application of the electric field, a transition to an organized fibrillar structure occurs. The density and thickness of the fibrils increases with the field strength and particle concentration and some branching is obviously observed. These effects are manifested through the increased agglomeration of particles, because higher field strength increases polarization, and enhances the attractive interactions of particles.

8.3 Gelation of Polythiophene ER Suspension Driven by Electric field

In this study, we have investigated the equilibrium rheological properties of suspensions of a conductive polymer, polythiophene, under the influence of electric field. The results show that the PTAA suspension exhibits viscoelastic behavior and a transition from fluid-like to solid-like behavior as the field strength is increased. The dependence of the G' on oil viscosity can be observed at the low to moderate electric field (0-100 V/mm). Unlike the loss modulus G", the dependence of the G" on oil viscosity can be observed at any particular field strengths, G" increased with increasing oil viscosity. Furthermore, it is observed that the equilibrium rheological properties of our PTAA suspensions satisfy the sol-gel transition Winter-Chambon criterion, in which tan δ becomes independent of frequency, when the sufficiently strong electric field strength is applied. The electric field strength for the transition has been found to decrease with increasing particle concentration. Moreover, the values of the power law exponent, n, are located in the range 0.05-0.83 depends on electric field strength. Finally, the fractal dimension value between 1.5 and 2.5 and it found to increase with the electric field strength.

8.4 Creep and Recovery Behaviors of Polythiophene-based Electrorheological Fluid

In this study, the creep and recovery behaviors of poly(3-thiopheneacetic acid) suspension has been investigated. Our results indicate that our ER suspensions behave like a viscoelastic solid under the electric field with a combination of elasticity, plasticity, and viscosity behaviors. With increasing stress, the fluids show instantaneous elastic response whereas the retarded elastic and the viscous responses decrease. After the removal of the applied stress, the strain decreases but does not completely relax to its original value which indicates that this fluid exhibits a partially elastic recovery. The elastic recovery response decreases with increasing stress and then disappears at some critical stress value, corresponding to the static yield stress. When the stress is increased above the yield stress, the fluid exhibits a purely liquid response in which the strain continuously increases with time.

Moreover, the equilibrium compliance parameters, J_C and J_R, were found to decrease with increasing particle concentration and particle conductivity. In both creep and recovery phases, the equilibrium compliance parameters at zero electric field, J_{Co} and J_{Ro}, strongly depend on the particle concentration and particle conductivity. The values of J_{Co} and J_{Ro} decrease with increasing particle concentration and particle conductivity. The creep *activation* electric field, E_C, and the recovery *activation* electric field, E_R, depend only on the particle conductivity but are independent of particle concentration. In addition, the recovery increases with the increasing of the electric field strength, particle concentration, and particle conductivity.

8.5 Recommendations for Future Work

The electrorheological properties of perchloric acid-doped poly(3-thiopheneacetic acid)/silicone oil suspension in both oscillatory and steady shear flow have been investigated in this work. The preliminary results of the hysteresis and creep behaviors of this suspension were done but not reported here. Although a series of ER properties of PTAA/silicone oil suspension has been carried out, more experiments, and especially dielectric properties of this suspension are interesting for further investigation to provide clarification and more understanding in the ER fundamentals. The relative polarizability of the system which governs the ER response is the one parameter that needs to be studied. This parameter is controlled by the conductivity mismatch between particles and continuous medium. Our results showed no difference of this parameter between lowly and highly doped systems, the variation of the relative polarizability by changing either solvent or dopant types are interesting for further observation.