CHAPTER VII
CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In the present research at which the extensive number of sample was examined, the properties of sewage sludge were studied as a potential resource in production of liquid fuel and chemical by pyrolysis, emphasizing on pyrolysis kinetics.

Compare to other solid materials, the sludge has low to moderate heating value, averaged of 9.7 MJ/kg, and has volatile matters of about the same as coal, 40 wt%. Whilst the existing solid fuels have a lower limit at 9.0 MJ/kg, in this case, the selection of sludge of above averaged quality for use in thermal process is recommended.

The correlation between heating value of sewage sludge and its proximate and ultimate analyses were found in the forms of following respective expressions (kJ/kg in dry-basis):

$$HHV = 255.75V + 283.88F - 2386.38$$

$$HHV = 430.2C - 186.7H - 127.4N + 178.6S + 184.2O - 2379.9$$

With these two expressions, the heating value prediction can be satisfied within the absolute error of less than 2%. The application of models is, however, less accurate for sewage sludge with the ash content of higher than 50%.

According to the thermogravimetric experiment, in general, the sewage sludge decomposition was found in range of 100-600 °C and not to limited in only one step. Based on a total number of 218 samples used in the study, the different decomposition behaviors were found, which can be classified into five patterns. As the temperature increase, the decomposition as sorbed moisture vaporization occurred at slightly higher than 100 °C. The main pyrolysis step occurs between 250 and 600 °C, which distinguish the behavior type for different sludges. Some samples also decompose at the temperature of more than 700 °C, whereas the calcium carbonate was degraded. Differences in the behavior may be due to different components in the sewage sludge both quantitatively and qualitatively. The second group (Types IV and V), which rarely found, has unusual properties. DTG peaks were found at 293, 388 and 481 °C for Type IV and 255 and 397 °C for Type V. Increasing heating rate from 5 to 20 °C/min can shift TG-DTG to higher temperature at which the overall curve patterns were not affected.

The kinetics of sewage sludge pyrolysis can be represented in form of either Pseudo single-, bi- or multi-component overall model. That means, the overall reaction can be modeled by a combination of single pseudo component decompositions. The activation energy of the first reaction, corresponding to the main pyrolysis typically at 300 °C, was rather constant (between 60.8 and 76.7 kJ mol^{-1}) whilst those of the second and third (as only in Type IV) reactions were varied in the range of 85.4–142.0 kJ mol^{-1}. A difference in the pyrolysis kinetics was laid on the second or third reactions. Typical order of the pyrolysis reaction was in the range of 1.1–1.8. The kinetic model used is useful for application with the satisfied results but the detail on each reaction was still not elucidated.

Later, the three evidences, TG-DTG analysis, FTIR spectroscopy and kinetic study, were provided to elucidate the sewage sludge pyrolysis by four decomposition reactions, each possibly contributed from an individual compound as the following scheme:

$$F_i \text{------------>} G_i + S_i, \qquad i = 1, 2, 3, 4$$

That means, there might be four fractions decompose separately in parallel. The apparent activation energies of sewage sludge constituent decomposition reactions were ca. 82, 121, 64 and 121 kJ mol^{-1}. First three were comparable to those of biomass species such as hemicellulose, cellulose and lignin. The first compound was also possibly explained by complex protein presented in bacteria. The remaining reaction, however, was probably contributed by extractive compound such as lipids, waxes and oil or even unknown. The reaction orders were found in between 0.91-

1.63, indicating the nature of sludge that somewhat deviated from biomass species. The results also showed the closely analogy between DTG curve of individual sludge constituents and those of biomass species. The FTIR spectra of raw sludge and extracted/digested residues also confirmed this proposal. The biomass species including the complex protein of bacteria cell wall might be based compositions of sewage sludge, which effluent to its pyrolysis property.

7.2 Recommendations

The primary study on mass and energy balances on pyrolysis system shows the worth-while possibility of a practical operation for converting the sewage sludge to liquid fuel and valuable chemicals. However, this work is only emphasized on the decomposition kinetics for which the reaction nature was elucidated. Nonetheless, a practical implementation needs a better understanding of generation of gas, bio-oil and solid products in accordance with the raw material disappearance. In this case, the study of product distribution and advances in equilibrium control is recommended.