Chapter 7

Conclusions and scope for future work

7.1 Conclusions

Some of the primary objectives of the present study includes:

- Torrefaction of biomass obtained from two different sources (agricultural residue and woody biomass) for the possible generalization of the torrefaction process on other biomass materials
- To establish the pros and cons related to the pyrolysis of torrefied biomass in comparison to their raw biomass pyrolysis
- Optimization, and the statistical analysis for both torrefaction and pyrolysis process using response surface methodology (RSM)
- Energy and exergy analysis of torrefaction and pyrolysis process in order to improve the existing process by introducing energy recuperation from by-products, and thus decreasing the energy consumption

Based on these objectives the experiments were held, whose results and their discussions were presented in the previous chapters and the important outcomes of the present study have been summarized as follows:

1. Statistical analysis revealed that during torrefaction the temperature had the most prominent influence on HHV and energy yield of torrefied biomass, followed by residence time and heating rate
2. The reduced quadratic models for predicting the HHV and the energy yield of the torrefied pigeon pea stalk and eucalyptus were efficient to operate within the designed space

3. The optimum operating conditions obtained for both the biomass were quite similar, and hence it can be recommended that the moderately severe torrefaction would be suitable for most of the biomass obtained either from agricultural residue or wood
4. The solid fuel properties of the torrefied biomass improved significantly as compared to their respective raw biomass. The torrefied biomass had much higher HHV, energy density and carbon content, on the other side contained lesser amount of oxygen, moisture and lean energy components
5. The torrefied biomass had much lesser moisture reabsorption capability as compared to raw biomass thus reducing the chances of biological degradation which makes it suitable in the storage for longer duration
6. The combustion indices for the torrefied biomass got enhanced significantly as compared to raw biomass which could be very useful in the field of co-combustion with coal for the existing power plants
7. Torrefied biomass were less in the ash content as compared to moderate grade coals which can be used to reduce the substantial amount of ash handling problems prevailing in coal based power plants and subsequently reducing the pollution in environment
8. Torrefied biomass in co-combustion with coal can also have a significant benefit in decreasing the NO_X and SO_X emission from coal based power plants as they have negligible sulfur content and lesser amount of nitrogen in them as compared to coal

9. The estimation of Kinetic parameters revealed that the total activation energy decreased significantly for moderate and severely torrefied biomass as compared to raw biomass
10. The organic part of the torrefaction liquid was rich in furan derivatives which could be used in the manufacturing of oxygen rich chemicals and adding to its economic value
11. During the pyrolysis of torrefied biomass the temperature had the most significant influence on the bio-oil yield as compared to other operating parameters
12. The optimum pyrolysis temperature (442.06 and 461.25 °C) for the torrefied biomass to obtain maximum bio-oil yield were close to each other suggesting that we can establish a generalised operating condition for the pyrolysis of torrefied biomass
13. The fuel properties like HHV and carbon content of the bio-oil from torrefied biomass increased while the water and oxygen content also decreased significantly as compared to bio-oil from raw biomass which suggests that the bio-oil from torrefied biomass could be a game changer in reducing the cost of bio-oil upgradation to transportation fuel
14. GC-MS analysis revealed that the bio-oil from torrefied biomass contained less amount of acid and higher amount of phenol, benzene and toluene derivatives which indicates the improved quality of bio-oil as compared to that of raw biomass

15. The yield of pyrolytic gas from the torrefied biomass changed marginally as compared to raw biomass, however, on the qualitative basis there was a significant improvement which can be utilized for the production of energy
16. Energy and exergy value of torrefied biomass have been highest followed by liquid and then torgas
17. Exergy efficiency of torrefied biomass has been in the range of 52 to 54% under moderate torrefaction which could be further increased by 8 to 9 % by recuperating of energy from byproducts (liquid and torgas)
18. The energy and exergy analysis for pyrolytic gas confirmed the significant increase in the chemical energy of CH_4 due its increased concentration which also confirms that the torrefied biomass as a feed for pyrolysis produces higher grade bio-fuels as compared to raw biomass pyrolysis
19. Total irreversibilities in the pyrolysis of torrefied biomass were much lesser as compared to raw biomass pyrolysis which confirms that torrefaction removes lean energy components during the pre-treatment process which helps in conserving useful energy to the pyrolysis products and decreasing the exergy losses

7.2 Future scope of work

- Further analysis regarding the reduction in ash handling, NO_X and SO_x by using torrefied biomass in co-combustion with coal
- Acid and alkaline pretreatment in combination with torrefaction to further reduce enhance the bio-fuel properties

- Design of catalyst to increase the bio-oil yield in the pyrolysis of torrefied biomass
- Improving the pelletization of torrefied biomass
- Utilization of torrefied biomass in gasification process and its impact on syngas production
- Utilization of waste heat from industries and power plants in torrefaction of biomass
- Hydrothermal liquefaction of torrefied biomass or biowaste so that minimum upgradation required for converting biocrude into transportation fuels
- Hybrid energy generation by coupling of solar energy in torrefaction process and its application in Organic Rankine Cycle (ORC)