Resin Degradation of End-of-Life Wind Turbine Blades to Produce Useful Chemical Compounds in the Context of Waste to Resource Recovery

H. Mumtaz[1](✉), S. Werle[1], S. Sobek[2], M. Sajdak[3], and R. Muzyka[3]

[1] Department of Thermal Technology, Silesian University of Technology, 44-100 Gliwice, Poland
hamza.mumtaz@polsl.pl
[2] Department of Heating, Ventilation and Dust Removal Technology, 44-100 Gliwice, Poland
[3] Department of Air Protection, Silesian University of Technology, 44-100 Gliwice, Poland

Abstract. The selection of proper strategies for degradation and useful product conversion of fiber composites is driven by various environmental and economic factors. Recycling end-of-life (EOL) waste of wind turbine (WT) blade composites is a critical challenge for the renewable energy sector because of its complex composition. The focus of this study is to degrade the complex resins of wind turbine blades to produce useful chemical compounds through the oxy-liquefaction technique under subcritical water conditions. Wind turbine blades have various resins including epoxy resins, glass fibers, and carbon fibers, and they are not easy to separate so the recovery of resin as an individual component is not an easy task. The treatment of selected waste material is carried out at the temperature range of 250 to 350 °C with starting pressure of 20 to 40 bar. The effect of varying weight percentages of oxygen, waste to liquid ratio and residence time on resin degradation has also been studied. Production of various chemical compounds including volatile fatty acids and benzene, toluene and xylene (BTXs) and their dependency on the extent of resin degradation have been checked by using analysis of variance (ANOVA) analysis. Identification of the various chemical compounds against different retention times and temperatures in gas chromatography with flame ionization detection (GC-FID) has also been presented. High resin degradation is an identification of the fact that the oxi-liquefaction technique has the potential to effectively treat the wind turbine blades and support the concept of waste to resource recovery.

Keywords: Wind turbines · Resin degradation · Volatile fatty acid production · Oxi-liquefaction

1 Introduction

Wind turbines are one of the most environmentally sound technologies for producing electricity, and wind energy has very low environmental impacts. The global wind industry is growing fast, in terms of both the number of turbines and their sizes [1]. According

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to the Global Wind Energy Council (GWEC) [2], modern turbines are 100 times the size of those in 1980. Over the same period, rotor diameters have increased eight-fold, with turbine blades surpassing 60 m in length [3]. Wind turbine blades typically consist of reinforcement fibers, such as glass fibers or carbon fibers; a plastic polymer, such as polyester or epoxy; sandwich core materials such as polyvinyl chloride (PVC), polyethylene terephthalate PET, or balsa wood; and bonded joints, coating (polyurethane), and lightning conductors. Wind turbine blades are predicted to have a lifecycle of around 20–25 years [4]. The question is what to do with them afterward. There are three possible routes for dismantling wind turbine blades: landfill, incineration, or recycling. In the modern era of science, landfilling and incineration are the least acceptable methods because of the number of cons associated with them. In the case of recycling, pyrolysis has the potential to solve the problem but being a high energy-intensive process and fewer chances of resource recovery the process is also not favorable [5, 6].

On the other hand, oxi-liquefaction is the process in which organic compounds are converted to low molecular weight organic acids in the controlled atmosphere of water in presence of oxidants at moderate temperatures and pressures [7]. Oxidants are compounds that decompose at a specific temperature and provide enough oxygen required for the oxidation of organic compounds present. The presence of oxidant makes the process more effective at lower temperatures and pressures [8].

Epoxy resins and glass fiber reinforced plastics (GRP) that are a major portion of wind turbine blades can affect the health of living organisms when they come in contact with skin, or if they evaporate or form a mist or dust in the air. The main effects of overexposure are irritation of the eyes, nose, throat, and skin, skin allergies, and asthma [3]. So the objective of this study is to check the potential of the oxi-liquefaction technique to reasonably degrade the epoxy resins and GRPs, to produce intermediate molecular weight organic compounds mostly volatile fatty acids. To relate the extant of resin degradation with fatty acids yield is also the objective of the study to support the concept of waste to resource recovery. Previously, almost no efforts have been made for resin degradation and value products from this type of complex solid waste. So, the current study offered oxy-liquefaction of the wind turbine as an emerging technique to sustainably degrade the complex resins with the aim of solid waste reduction and valuable product generation.

2 Materials and Methods

The pieces of wind turbine blades were collected from ANMET company whose sole purpose is recycling the waste and these pieces were further cut mechanically into small pieces varying in size between 1 and 2 cm and mixed with water and hydrogen peroxide in suitable proportion according to the experimental conditions. Parr 4650 reactor was used to carry out the experiments at a set temperature and pressure conditions. Nitrogen gas played its role to provide an inert environment and maintain the required pressure inside the reactor. Experiments were performed between 250 and 350 °C, at a pressure range of 20–40 bar. The three retention times 30, 60, and 90 min, concentrations of H_2O_2 (15%, 30%, and 45%), and waste/liquid ratio (5%, 15%, and 25%) were also tested in these experiments. The characteristics of wind turbine blades used in these experiments have been provided in Table 1. GC-FID was used to identify the various chemical products in the solution that has been already adopted in available studies for determining the products of pyrolysis [9–11]. ANOVA analysis through statisca software has been used to identify the type of relation between total resin degradation and VFAs productions by calculating the value of correlation factor "r" whose positive values show the direct relation while negative values show the indirect relation between the tested quantities [12].

Table 1 Results from Ultimate and proximate analysis of wind turbine blades

Parameters	Concentration (%)	Parameters	Concentration (%)
Moisture content in the analytical state (M_{ad})	1.31	Content of total carbon in the analytical state (C_{ad})	28.21
Ash content in the analytical state (A_{ad})	56.9	Content of total hydrogen in the dry state (H_a)	2.71
Volatile matter (VM)	40.71	Content of nitrogen in the analytical state (N_{ad})	1.20
Content of total sulphur in the analytical state ($w_{S, ad}$)	< 0.1	Content of oxygen	8.0

3 Results and Discussions

3.1 Resin Degradation and Production of Fatty Acids

As the result of the oxy-liquefaction process, a large content of resins 48 percent of the total weight has been degraded successfully, but this degradation of resin is dependent upon applied pressure, temperature, the concentration of H_2O_2, and waste to liquid ratio, this dependency is in agreement with one provided by Suresh K. Bhargava while explaining wet oxidation and catalytic wet oxidation in details [7]. Experiments showed that out of all these mentioned parameters the resin degradation is highly dependent upon the waste/liquid ratio. Lower waste to liquid ratio results in higher degradation of wind turbine resins that are highly organic in nature and result in the production of volatile fatty acids (VFAs) and BTXs compounds. Oxidative degradation of organic compounds like resins results in the formation of aldehydes, ketones, and alcohols, which are further oxidized to volatile fatty acids.

The formation of VFAs is highly dependent upon the extent of degradation of solid resins, a greater extent of degradation will result in a higher concentration of various acids. The validation of this fact is also shown in Fig. 1, where the percentage of resin degradation has been plotted against the total amount of VFAs produced. Co-relation value 'r' is very close to 1 showing that the tested quantities have a strong influence on each other, and a positive sign shows there is a direct relation between them.

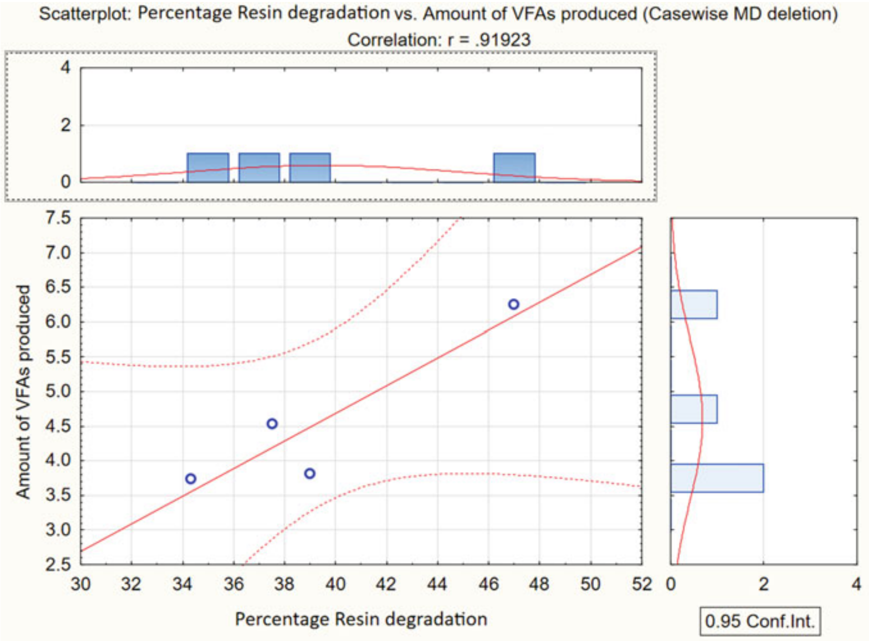

Fig. 1 Dependency of total VFAs production on percentage resin degradation

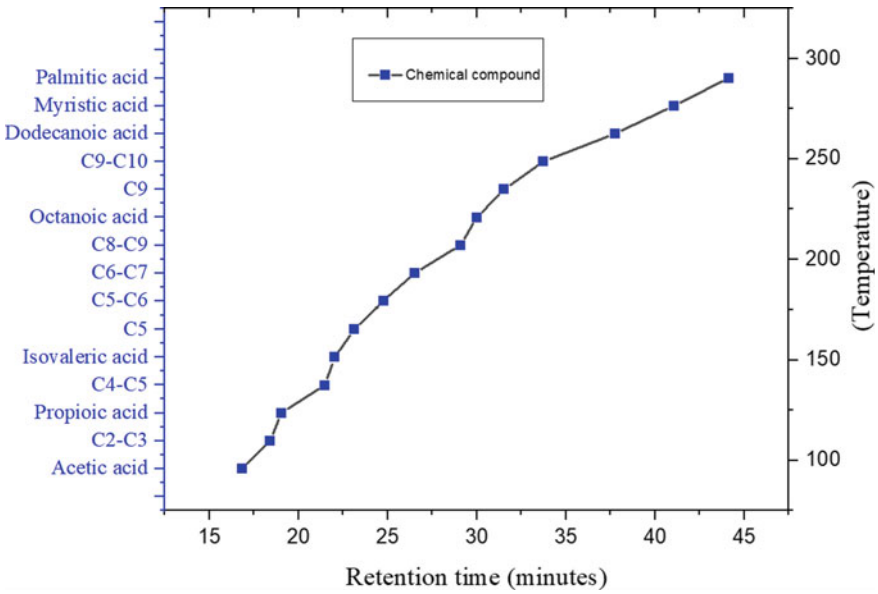

Fig. 2 Identification of various chemical compounds against different retention time and temperature

Identification of various compounds against increasing temperature and increasing retention time in GC-FID can be seen in Fig. 2.

The first compound that appear in the results at the minimum temperature was acetic acid. That is the major concern of a number of studies reported [13, 14]. Later there are various compounds that can be seen against the different retention times and temperatures but the special compounds with carbon numbers mentioned for example C_2–C_3 are the compounds that have not been identified clearly by GC-FID analysis, but it is confirmed they have the number of atoms between 2 and 3, similarly the number of carbon atoms are between 4 and 5 for a compound mentioned with the name C_4–C_5. In the presence of peroxide, the oxidation of organic compounds is supposed to follow the mentioned scheme.

$$H_2O_2 \rightarrow HO^{\cdot} + HO^{\cdot} \tag{1}$$

$$O_2 \rightarrow O^{\cdot} + O^{\cdot} \tag{2}$$

$$H_2O + O^{\cdot} \rightarrow HO^{\cdot} + HO^{\cdot} \tag{3}$$

These three reactions are the initiation reaction that generates the free radical to decompose the long chains of organic compounds.

$$RH + HO^{\cdot} \rightarrow R^{\cdot} + H_2O \tag{4}$$

$$R^{\cdot} + O_2 \rightarrow R - O - O^{\cdot} \tag{5}$$

$$R - O - O^{\cdot} + RH \rightarrow R - O - O - H + R^{\cdot} \tag{6}$$

The organic hydroperoxide that is produced in step (7) is unstable and highly reactive which plays an important role in acid formation, hydroxyl radical cycling and secondary organic aerosol formation.

$$2R - O - O^{\cdot} \rightarrow R - O - O - R + O^2 \tag{7}$$

Steps represented by the Eq. (4) to (6) are intermediate steps of the conversion mechanism, and Eq. (7) represents the termination step. This mechanism is very similar to the one proposed by [15].

4 Conclusions

Oxy-liquefaction technique can effectively degrade organic resins in wind turbine blades that are dangerous to the environment. During oxi-liquefaction, resins are degraded, BTX and volatile fatty acids are produced and their concentration is widely dependent upon the temperature, pressure, weight percentages of oxygen, waste to liquid ratio, and residence time. Maximum resin degradation i.e., 48% is observed when the waste/liquid ratio was minimum. Total resin degradation is directly related to the production of VFAs, so the chances of formation of other less desirable compounds are less expectable. Obtained results suggest that the oxi-liquefaction technique has the potential for resin degradation of the WTB for value-added products generation but the further results from GC-FID analysis will help us to propose the dependency of concentration of individual components on various factors and interconversion against the increasing temperature and oxygen percentage. The future studies will be focusing on examination the effects of the size of WTB chips in sample preparation, other temperatures, residence times, and waste-to-liquid rations, and also co-liquefaction with biomass, as an oxidizer alternative to the hydrogen peroxide.

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