1. Introduction

Fossil fuels are the world’s primary source of energy, in the world, accounting for more than 80% of global energy consumption. Overconsumption of this non-renewable energy contributes to global warming due to the massive emissions of greenhouse gases. The problems related to fossil fuels and the serious environmental concerns have motivated people’s efforts towards sustainability and enhanced engagement in green technology.

Biomass is considered one of the key solutions for our alternative energy needs. Roughly approximately 90% of biomass is disposed of as waste in the palm oil industry in Malaysia. In addition, 351 palm oil mills in Malaysia produced 30 million tonnes of empty fruit bunches (EFB) from 83 million dry tonnes of solid biomass in 2012. The abundance of underutilised biomass feedstock which are underutilised has gained growing interest among researchers as a potential solid fuel energy resource.

However, biomass feedstock cannot be directly feed into the existing combustion system due to its unfavourable properties, such as low calorific value, high moisture content and reduction in quality via biodegradation. The biomass requires a prior pre-treatment, which is achieved through a process known as torrefaction, to enhance its quality as a solid fuel. Torrefaction is a lignocellulosic biomass pre-treatment process at low temperatures between 473 K and 573 K under an inert atmosphere. It is a cheap technology but it needs additional operating costs due to the need for thermal energy and nitrogen as a carrier gas. If torrefaction could be carried out in the presence of oxygen, this would reduce the operating expenses by utilising flue gas from the burners. Therefore, this study aims to investigate the effects of oxygen towards the torrefaction of EFB.

2. Experimental

The biomass residues used in this study were the consisted of empty fruit bunches (EFB) which were collected from Felcra Nasaruddin Oil palm mill in Bota, Perak, Malaysia. Prior to the torrefaction treatment, EFB were first chopped into smaller sizes and dried at 105 °C overnight to remove the moisture. These EFB were then grounded and further sieved to obtain a uniform particle size ranging from 0.25 mm to 0.50 mm.

The experimental system where the torrefaction process was conducted consisted of a vertical tubular reactor made of stainless steel with an internal diameter of 0.028 m and a length of 0.56 m, where the torrefaction process was conducted. The torrefaction reactor was connected to a condenser which was immersed in ice cubes in order to collect the condensable gases (Figure 1). A 5-g sample of empty fruit bunches sample was placed in the centre of the reactor supported by a glass wool and held with wire acting as its supporter and holder respectively. Then, the system was flushed with torrefaction gas for 15 minutes with a flow rate of 100 mL/min. After the system was flushing the system, the flow rate of torrefaction gas was reduced to 30 mL/min and the temperature of the reactor was raised from room temperature to the desired temperature using an electric furnace at a rate of 10 °C/min. Once the desired temperature was reached, the torrefaction temperature was maintained for 30 minutes. The torrefaction process produces solid,
liquid and non-condensable products. When cooled, the solid torrefied biomass was retrieved later from the reactor after it has cooled down and being weighed. The condensed vapour phase was collected in a condenser and weighed. The solid yield is an important indicator when evaluating the severity of the torrefaction condition towards biomass. It can be calculated as in the following equation:

\[ Y_m = \frac{m_{\text{torrefied}}}{m_{\text{raw}}} \times 100\% \quad (1) \]

where \( Y_m \) is the solid yield, \( m_{\text{torrefied}} \) is the mass of torrefaction products and \( m_{\text{raw}} \) is the mass of torrefaction reactants. All weights reported were based on a dry basis.

The bulk densities of the untorrefied and torrefied biomass were determined by measuring the mass of a known volume of EFB sample, which was placed in a measuring cylinder. Then the density was measured based on the known volume and mass obtained.

The calorific values were determined using a bomb calorimeter, model C2000 series manufactured by IKA Werke. The obtained calorific value was produced from the sample.