Condensation of the hot volatiles from waste tyre pyrolysis by quenching

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Two techniques for cooling and condensing the hot volatiles to produce tyre derived oil (TDO) from a waste tyre pyrolysis reactor were compared, i.e., conventional tube-and-shell heat exchanger type condensation, and quenching condensation by direct contact between the hot volatiles and quenching water. Exchanging the tube-and-shell condenser with direct quenching condensation increased the total TDO yield. Additionally, application of the quenching condenser increased the δ- and l-isomers of limonene (δ-limonene) yield from 7.6 to 7.9 wt.%, while the benzothiazole concentration (a sulphurous and nitrogenous compound) in the TDO was decreased by 60%. The optimal operating conditions for quenching condensation were a quenching water volume of 2.1 L (a 50:1 weight of water to weight of tyre crumb ratio) and a spraying flow rate of 0.96 L/min. Additionally, the quenching condenser unit worked as a gas cleaner by wetting and trapping soot and fine solids from the non-condensable gases.

1. Introduction

High content of carbon and hydrogen elements in waste tyre results in its pyrolysis being a potential means to produce energy, materials and chemicals [1]. Waste tyre pyrolysis is the thermal devolatilisation of the organic compounds present in the waste tyre under inert conditions to produce gaseous, liquid and solid products. Among the three products from waste tyre pyrolysis, i.e., (pyro) gas, tyre derived oil (TDO) and (pyro) char, TDO is potentially the most valuable fraction, since it can be used for both energy recovery and for the recovery of valuable chemical products (e.g. dipentene or δ-limonene) [2]. In order to maximise economic potential of the TDO, the valuable chemicals concentration should be maximised, while the concentration of the heteroatom compounds (nitrogen, oxygen and sulphur containing) should be as low as possible to use the TDO as a fuel.

The quality of the TDO, which is generally low compared to diesel fuels, is typically influenced by the techniques used to cool and condense the hot volatiles from the pyrolysis reactor. The conventional technique for condensation consists of tube-and-shell type heat exchangers connected in series (condensation train) as the primary unit for gas cooling and condensing [3–6]. Using a tube-and-shell heat exchanger to cool and condense the hot volatiles from the pyrolysis reactor results in a TDO that has high amounts of nitrogenous (1.35 wt.%) and sulphurous (0.89 wt.%) compounds [7,8]. These compounds are products of the thermal devolatilisation of processing additives (mostly benzothiazole) and sulphur-containing vulcanisation agents used in the tyre formulation/manufacturing [7,9]. In addition, TDO typically contains char, sand and alkali metals as well as tar and polymers in the form of gumming materials [10]. Therefore, TDO typically has a higher viscosity and sulphur content compared to conventional fuels [11]. Moreover, nitrogenous compounds in the TDO are undesirable because during refining to higher quality fuels, these compounds may poison catalysts and promote gum formation [7,12]. Viscosity and sulphur content of the TDO influences the combustion efficiency and emissions, respectively [13]. Finally, the presence of polymers, tars and solid particles in the TDO may cause formation of deposits in the liquid fuel injection system.

The quality of crude TDO can be improved through various modification methods, such as, i) removal of moisture, ii) desulphurisation, and iii) distillation [13–16]. Murugan et al. upgraded TDO by firstly evaporating moisture, followed by desulphurisation through addition of hydrosulphuric acid, and finally by distillation, resulting in an improved TDO with a higher calorific value [17]. Lopez et al. used distillation simulations to propose a method to reduce the sulphur content of the TDO [18]. Chen et al. reported that TDO contains heteroatom compounds, such as, alky benzothiophene and a variety of sulphoxides and sulphones compounds [12]. They also observed sulphur removal from TDO with an effi-

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ciency of 80% when using solvent extraction with acetonitrile as the solvent. Conversely, Murenza observed that only about 1% of the sulphur originally included in the tyre, was detected in the TDO [19]. They assumed that the remaining sulphur evolves as H2S in the (pyro) gas phase. Some other techniques for TDO desulphurisation include i) catalytic pyrolysis, ii) hydrogenative pyrolysis, iii) ultrasound-assisted oxidative desulphurisation, and iv) solid adsorption [12,15,19]. However, the chemical composition of the TDO is typically complex, consisting of a plethora of compounds. For example, benzothiazole was reported as the main heteroatom compound (2.28 wt.%) in TDO by Frigo et al. [20]. Therefore, a TDO with lower concentration of heteroatom compounds is highly desirable.

Nevertheless, upgraded crude TDO cannot commercially compete with petroleum-derived fuels at current relatively low oil prices [21]. To improve the competitiveness of the TDO as a fuel, many researchers are investigating novel methods to maximising valuable chemicals (e.g. limonene) recovery from TDO, and then use the remaining TDO as a fuel [22–25]. Limonene is a valuable chemical in the TDO, with an estimated price at 2 US$/kg [2]. Therefore, limonene yield and concentration in the TDO should be maximised.

The objective of the present study is to investigate the effect of replacing a conventional tube-and-shell heat exchanger for condensation of hot volatiles from the pyrolysis reactor, with quenching condensation. The impact on total TDO yield, limonene yield and concentration and benzothiazole concentration in the TDO will be considered. The present study focuses on water as a quenching fluid, as it is a relatively cheap, readily available and good medium for energy transfer (cooling of hot volatiles). Moreover, the effect of the amount of quenching water used and the rate of spraying will be investigated.

2. Methodology

Waste tyre crumb (steel- and fabric-free) with particle size ranging between 2.8 and 3.4 mm were isolated by sieving from a bulk sample (500 kg), consisting of up to 5 mm particle size and supplied by a local waste tyre recycler. The waste tyre crumb was similar to feedstock used previously for pyrolysis process development [26]. Proximate analysis was conducted using a slightly adjusted version of ASTM E1113–08 (with X = 275 °C) [26]. The results of the proximate analysis are shown in Table 1.

A sample size of 40 g waste tyre crumb was fed in the pyrolysis reactor. The preferred operational conditions, suitable for a maximum limonene yield in the TDO, were similar to those established from previous work, i.e., a final pyrolysis temperature of 475 °C, a heating rate of 20 °C/min, and a pyrolysis time of 60 min [26]. The hot volatiles were purged out from the reactor with nitrogen gas (99.5% purity, Afrox, South Africa) at a constant flow rate of 1 NL/min. The same operating conditions were applied to the two different condensation units, in order to determine the effect of those units.

Two types of condensation units, i.e., a tube-and-shell heat exchanger condensation train and a water quenching direct-contact condenser, were compared for cooling and condensation of the hot volatiles from the pyrolysis reactor. Each condensation unit was connected to the horizontal (850 mm long, 60 mm OD) quartz tube pyrolysis reactor. The source of heat in the pyrolysis reactor furnace consisted of six well-insulated heating elements. The pyrolysis reactor, as connected to the tube-and-shell heat exchanger type condensation train, is shown in Fig. 1. The tube-and-shell condensation train consisted of five tube-and-shell heat exchangers each maintained at a pre-determined temperature. The first condenser was maintained at ambient temperature. The subsequent condensers (two to five) were maintained at a temperature of −10 °C using ice-dry ice slurries. Similar to the conventional tube-and-shell heat exchanger condenser, the hot volatiles were cooled and condensed to yield the TDO without physical contact with the cooling fluid.

The pyrolysis reactor connected to the quenching condenser is presented in Fig. 2. The quenching condenser tower replaces the tube-and-shell heat exchangers. Quencher condensation entails direct contact of the hot volatiles from the pyrolysis reactor with the quenching liquid, which is injected through a spraying nozzle. The hot volatiles from the pyrolysis reactor are introduced at the upper half of the quenching tower through the inlet pipe connected to the pyrolysis reactor. This pipe is maintained at a temperature of 200 °C, to prevent condensation of the hot volatiles. The quenching liquid was demineralised water, introduced at the top of the quenching tower using a spraying nozzle. The nozzle is a standard type, 0.635 cm NPT removable cap male made from stainless
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