Computational modelling of the condensation of fast pyrolysis vapours in a quenching column. Part A: Hydrodynamics, heat transfer and design optimisation

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A B S T R A C T

Direct contact heat exchangers (quenching columns) are considered to be the optimum types of heat exchangers for the fast pyrolysis process. In this study, the hydrodynamics and heat transfer characteristics of a bench scale quenching column are presented. These have been compared with the experimental observations on flooding phenomena which are reported when the quenching column is operated at the design gas flow rates of the fast pyrolysis reactor. The quenching column was found to operate without flooding at 10% of the design flow rate, while flooding was still present even at 50% of the design gas flow rate. Four different design configurations, which are different in terms of weirs and hole placement on the disc and donut plates, are modelled and tested under full gas flow rate conditions. All four cases show normal quenching column operation without any flooding phenomena present and a gas flow time of less than 1 s. The pressure drop across the system was considerably reduced to 15Pa in the modified configuration compared to 90Pa in the baseline model. The hydrodynamic and heat transfer characteristics are thoroughly analysed and proposed optimal design configuration for the effective quenching operation.

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1. Introduction

Fast pyrolysis presents certain advantages over other biomass thermochemical conversion methods in generating liquid fuels (bio-oil). Compared to other renewable energy sources, that can produce heat and power, biomass represents the only source for liquid, solid and gaseous fuels. The biomass pyrolysis process can provide a liquid fuel that can be a substitute for fossil fuel oil in any static heating or electric generation application [1].

Liquid bio-oil is produced by the rapid condensation of pyrolysis vapours in heat exchangers. Several types of heat exchangers are available for this purpose, ranging from simple indirect contact heat exchangers to more complicated and sophisticated quenching columns. The presence of non-condensable gases in the system poses significant resistance to the heat and mass transfer, thereby forcing the conventional indirect contact heat exchangers to larger sizes. Indirect contact heat exchangers can also cause preferential deposition of lignin-derived components, leading to liquid fractionation and eventually blockage of the pipelines and consequently the heat exchanger itself [2]. Quenching is a direct contact heat exchanging process in which gases and vapours come in direct contact with the liquid coolants.

Quenching columns can be used in the pyrolysis vapours condensation process to obtain liquid bio-oil. For this purpose, immiscible hydrocarbon solvents or even recirculated liquid bio-oil are usually adopted as the cooling media. The advantages in using quenching columns for the condensation of pyrolysis vapours are numerous. High heat transfer rates can be obtained by the direct contact of the two working fluids, as well as the greater amount of gas scrubbing that can be achieved. These factors might lead to the complete removal of the electrostatic precipitators (ESP) from the liquid collection system (LCS). This contributes in the reduction of the overall cost of the process, while making it more economically viable on a large scale.

From the process point of view, rapid condensation of pyrolysis vapours is necessary to increase the final bio-oil yield [3–6]. According to Bridgwater [7], an essential feature of a fast pyrolysis system for producing liquid fuels, apart from the high heating rates and the carefully controlled temperature in the reactor zone, is the low residence time of the vapours associated with its rapid cooling. The residence time of the vapour refers to the time taken from the vapour generation in the reactor to their final condensation in the liquid collection system. The optimum vapour residence time is typically 2 s for the fast pyrolysis process, in order to minimise the undesirable secondary reactions that take place in the vapour phase. Secondary cracking tends to increase the content of non-condensable gases in the expense of the final liquid bio-oil [8,9]. The design of efficiently operating quenching columns, using

empirical relations, becomes extremely difficult due to the high complexity of the physical phenomena involved in the process. The gas–liquid interactions, both in terms of momentum and heat transport, result in complex flow regimes inside the quenching column, something that is difficult to be predicted by experimentation alone. Under these considerations, the employment of computational methods to provide an insight on the physical phenomena present in the process (i.e., hydrodynamics, heat transfer and phase change phenomena) becomes necessary.

Various modelling studies have been undertaken in the modelling of the hydrodynamics of sieve tray columns [10–13]. So far, most of the modelling studies done in the field of pyrolysis technologies are either particle dynamics [14] or chemical conversion modelling [15] within the fluidised bed reactors. However, to the best of our knowledge, only a single research study has been conducted in the modelling of the condensation of pyrolysis vapours on a double surface condenser [16]. In that study, the condensation of a mixture of pyrolysis vapours, in the presence of non-condensable gases, is simulated in an indirect contact heat exchanger. The vapours are treated as ideal gases, while the vapour mixture is treated as a unique phase without distinct chemical species. The latter assumption imposes a restriction on the selective condensation of species in different temperatures, thus leading to a predefined composition of the final bio-oil product. The authors have not identified a single study on the numerical modelling and simulation of the condensation of fast pyrolysis vapours in quenching columns.

In this study, a first attempt on the modelling of the hydrodynamic and heat transfer phenomena with the aim of eliminating the flooding issues of quenching columns is presented. The gas liquid interactions are simulated using the immiscible Eulerian–Eulerian approach. The CFD studies showed the flooding phenomena, occurring at 50% of the design gas flow rate, while it is shown that the column can normally operate at 10% of the design gas flow rate. Both of these conditions were reported in the experimental investigations [17]. Under these considerations, four alternative design configurations are presented and modelled. The results are thoroughly analysed and discussed in terms of both hydrodynamic and heat transfer performance.

2. Quenching column operating conditions

Experimental investigations have been conducted at Aston University, based on the ablative pyrolysis process described by Peacocke et al. [18], for the production of liquid bio-oil (Fig. 1). The pyrolysis reactor is designed to operate at a biomass feeding rate of 5 kg/h; however, the feeding rate was limited to 3 kg/h due to feeder limitations. The liquid collection system of the pyrolysis rig composed of a quenching column coupled with an electrostatic precipitator. The dimensions of the quenching column (Fig. 2) are based on the maximum intended gas flow rates (Table 1) from the pyrolysis reactor, as well as the flooding factors.
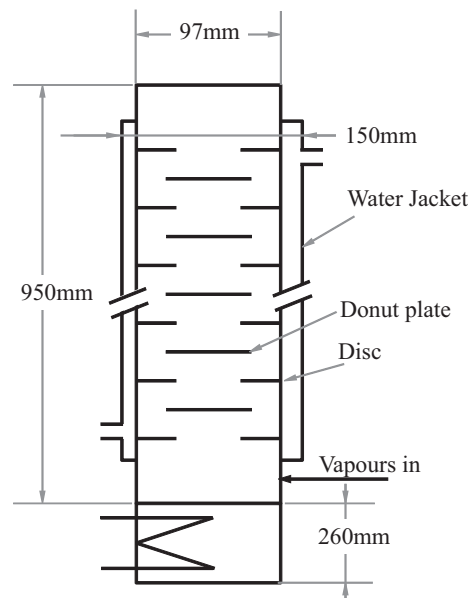

Fig. 2. Original (baseline) design of the experimental quenching column.

The equipment has been designed for a total gas (i.e., gases plus pyrolysis vapours) flow rate 0.0044 m^3/s with a temperature of 673 K. The gaseous composition was estimated based on Toft's [19] empirical relationship. Thus, the total gas composition consists of 87% N_2, 7% water vapour, 4% non-condensable gases and 1.5% organics, by volume. The experimentation was done on beech wood, and final product yields were 64.9% liquids, 13.83% char, 12.37% gases and 10.4% moisture by mass excluding the carrier gas. Octane at 268 K has been used as the direct contact cooling medium because of its immiscibility with the highly oxygenated hydrocarbons present in the final liquid bio-oil product. The experimental findings reported flooding of the quenching column at the design gaseous flow rate of 0.0044 m^3/s. The problem was finally resolved by lowering the liquid coolant flow rate and by reducing the diameter of the discs. However, these modifications severely affected the quenching capacity of the equipment. It was also reported that the original quenching column design could only operate normally when the gaseous flow rate was reduced to 10% of its original design value. Flooding was reported for any gas flow rate above this value.

3. Numerical model

The commercial CFD package ANSYS Fluent 14 has been used as the computational platform for the simulation of the quenching column hydrodynamics. The modelling approach is based on the immiscible Eulerian model (VOF and Eulerian Multiphase model), which is able to track the interface between two immiscible phases, while providing
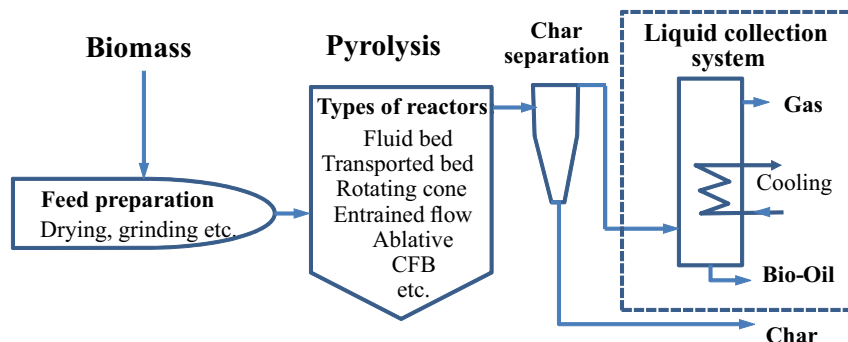

Fig. 1. Fast pyrolysis process flow diagram.