Fuel Processing Technology 133 (2015) 97–104

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Vegetable oil as a solvent for removing producer gas tar compounds

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ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form 17 December 2014
Accepted 30 December 2014
Available online 24 January 2015

Keywords:
Producer gas tars
Raschig rings
Wet scrubbing system
Soybean oil
Canola oil

ABSTRACT

The objective of this study was to evaluate the performance of vegetable oil as a solvent in a wet packed bed scrubbing system for removing model producer gas tar compounds. Solvent type, column bed height, solvent temperature and solvent flow rate were varied to assess the performance in terms of tar removal efficiency. Soybean and canola oils were used as solvents. Benzene, toluene and ethylbenzene were used as model tar compounds. Testing was conducted using a bench scale packed bed column, 5.25 cm diameter by 1.1 m height, filled with 6-mm raschig rings as packing material. Statistical analysis showed that soybean and canola oils provide comparable removal efficiencies of tar compounds. The analysis also revealed that bed height and solvent temperature had highly significant effects on tar removal efficiencies. Bed height, solvent temperature and solvent flow rate had highly significant effects on liquid holdup and pressure drop across the column.

1. Introduction

The demand of lignocellulosic biomass, a renewable feedstock, has increased due to an emphasis towards the production of biofuels [1]. One of the pathways of biofuels production is through thermochemical conversion which involves the gasification of biomass followed by the conversion of producer gas to biofuels through biocatalysts or chemical catalysts. The conversion of producer gas to alcohols through biocatalysts is one of the major research programs at Oklahoma State University [2]. The key challenge of the gasification technology is the production of low-tar producer gas for the microbial catalysts.

Tars are the higher molecular weight hydrocarbons formed through thermal or partial-oxidation of organic material. Tars condense or polymerize into more complex structures in the downstream equipment that can lead to chocking and attrition. Consequently, the system efficiency decreases and the maintenance of the system increases. The stated tolerance limit of tars for various applications is 50–500 mg/Nm^3 for compressors, 50–100 mg/Nm^3 for internal combustion engines, 5 mg/Nm^3 for direct fired gas turbines, and <0.1 mg/Nm^3 for methanol synthesis [3–5]. Therefore, the removal of tar compounds is important for the successful application of producer gas for most processes.

Catalytic and thermal cracking and mechanism methods are the main downstream methods for tar removal [6]. Mechanism methods, such as scrubbers, cyclones, and filters, are preferred due to low energy requirements. Among these mechanism methods, wet scrubbing technologies are widely reported as an effective method for the tar removal [6].

Extensive studies on various types of water based wet scrubbing processes for removing tars have been reported in the literature; whereas, little information is available on wet packed bed scrubbing systems [7,8]. Bhave et al. [7] developed a water-based scrubbing system which combines wet and dry-packed bed scrubbing sections in a single unit. The wet packed bed column consisted of 15-mm raschig ring bed of 40 cm high (bottom), 15 to 30-mm pebbles bed of 10 cm high (middle) and 6-mm raschig ring bed of 20 cm high (top). The system was tested for 50 m^3/h producer gas generated through a throatless downdraft gasifier. Producer gas tar and particulate removal efficiency using the packed bed scrubber varied from 70% to 90%. Another study reported on the development of an oil-based gas washer technology for the removal of producer gas tars [8]. Researchers reported a reduction in producer gas tar concentration from 7000 to 50 mg/Nm^3. However, the details of the packed bed scrubbers and oil types were not provided.

A few research studies have been reported on wet scrubbing systems for the removal of volatile organic compounds (VOCs). Ozturk and Yilmaz [9] studied fresh and waste vegetable, and lubrication oils as solvents in a bubble column to remove VOCs consisting of benzene, carbon tetrachloride, methanol and toluene. They reported waste oils could be cost competitive solvents for the removal of VOCs.

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http://dx.doi.org/10.1016/j.fuproc.2014.12.046
0378-3820/

Phuphuakrat et al. [10] reported that fuel oils, such as diesel and plant-based biodiesel fuels, in a bubble column reactor showed high removal efficiency for tar compounds; however, the loss of solvent due to high volatility was the major issue, resulting in fuel oils not recommended as solvents.

The major parameters influencing absorber performance include liquid flux, gas flux, concentration of pollutants, and concentration of absorbent solution. Further, type and size of packing material, method of packing, liquid distribution, viscosity of solvent, solvent temperature and bed height also affect the performance of the absorption system [11–15].

As per the published studies indicated above, water based wet scrubbing systems have several major drawbacks, including a low absorption capacity of tar compounds in water and costly waste water treatment. Based on preliminary studies, vegetable oils showed potential as solvents for the removal of tars owing to characteristics of high absorption capacity for tar compounds. Vegetable oils are renewable in nature and, being plant-based, are CO_2 neutral, less volatile, low cost and hazard free. However, there is no study reported on a vegetable oil based wet packed bed scrubbing system for the removal of tars. The objective of this study was to evaluate the performance of vegetable oil as a solvent in a wet packed bed scrubbing system for the removal of model producer gas tar compounds.

2. Materials and methods

2.1. Materials characterization

2.1.1. Vegetable oil (solvent)

Vegetable oils consist of saturated (palmitic and steric acids) and unsaturated acids (oleic, linoleic and linolenic acids). Soybean and canola oils are selected as the vegetable oils for this study because these are low in saturated fatty acids. Oils high in saturated fatty acids convert to solid state at room temperature. The properties of soybean and canola oils, as purchased from Jedwards International, Inc., Quincy, MA, are shown in Table 1. The numbers in the bracket of each fatty acid represent carbon atoms and double bonds. For example, oleic acid (18:1) means that this acid has 18 carbon atoms and one double bond.

2.1.2. Model tar compounds

The model producer gas tar compounds used in this study were benzene, toluene and ethylbenzene. The purity of benzene, toluene and ethylbenzene, as procured from Sigma Aldrich Inc., Atlanta, GA, was 99.5%, 99.7%, and 99.8%, respectively. Properties of these compounds provided by Sigma Aldrich Inc. are shown in Table 2.

2.2. Experimental set-up

The design and construction details of the wet packed bed scrubbing system are given in Bhoi [16]. The experimental set-up of the system (Fig. 1) consists of two major sections: gas mixing and packed bed absorption column. Gas mixing section involves injection of known masses or volumes of tar compounds in a hot air stream to achieve a desired concentration of tar compounds. It consists of compressed air line, on/off valve, pressure regulator with a pressure gauge (Grainger, Roanoke, TX), air flow switch (Gems Sensors Inc., Plainville, CT), mass flow controller (Aalborg Instruments and Controls, Inc., Orangeburg, NY), heater with temperature controller (Tutco-Farnam Custom Products, Arden, NC), check valve (Swagelok Oklahoma, Tulsa, OK), syringe pump (KD Scientific, Holliston, MA), and rupture disc (McMaster-Carr).

Tar compounds mixture was prepared by weight distribution (benzene: 50%, toluene: 30%, and ethylbenzene: 20%) which is comparable to tar compounds collected by Cateni [17] from a fluidized bed gasification system. The tars mixture was injected using 100-ml gas-tight syringe with luer lock needle (SGE Analytical Science, Austin, TX) and syringe pump KD Scientific, Holliston, MA.

The packed bed absorption column was fabricated using stainless steel pipe of nominal 2-inch (schedule 40). The diameter and height of the packed bed column were 5.25 and 110 cm, respectively. The column was randomly filled with 6-mm raschig rings (Raschig Jaeger Technologies, Arlington, TX). The 0.8-l sump of the packed bed column was submerged in hot water bath (Grainger, Roanoke, TX) to maintain a desired solvent temperature. The solvent, i.e., vegetable oil, was uniformly distributed on the top surface of the packed bed using solvent recycling pump, i.e., peristaltic pump (Harvard Apparatus, Holliston, MA), and using a specifically designed liquid distributor. The heat loss from the column was minimized by insulating the packed bed absorption column using 6.5 mm thick fiberglass pipe insulation (McMaster-Carr). The solvent pipe was wrapped with a high-temperature heat cable with temperature controller (McMaster-Carr) and insulated using 2.5 cm flexible ceramic insulation to maintain the desired solvent temperature.

2.3. Experimental design and statistical analysis

The range of test conditions is provided in Table 3. A 3 × 3 factorial in a split plot arrangement in a randomized complete block design was used for the bed heights of 0.5, 0.8 and 1.1 m for soybean oil. Because the performance of soybean and canola oil at 0.5 m was not significantly different, only the 0.5 m bed height was evaluated for canola oil.

For the statistical analysis, slopes of the response of tar compounds (benzene, toluene and ethylbenzene) to time were calculated with a least square regression for each combination of replication, solvent type, bed height, solvent temperature and solvent flow rate. Significance of differences in slopes was determined using analysis of variance (ANOVA) procedure considering a split plot model.

In this study, the analysis was conducted separately for each vegetable oil type, packed bed height was the main unit factor, and solvent temperature and solvent flow rate were the split unit factors. Two replications (blocks) of each experimental condition were performed.

2.4. Test procedure and measurements

Initially, the sump was filled with 800 ml of vegetable oil. The water bath heater was started to maintain the desired solvent temperature. Air was then supplied and maintained at 0.65 m^3/h with the operating pressure set at 20 psig measured using a pressure regulator. Once the air flow rate was confirmed through the mass flow controller, the heater started to heat the incoming air to 350 °C which was maintained using the temperature controller. When the oil in the sump reached the desired temperature (about 30 min), the circulation pump was started.

Table 1
Properties of vegetable oils [16].

Parameters	Soybean oil	Canola oil
Palmitic acid (16:0), %	9	4.8
Steric acid (18:0), %	4.4	1.8
Oleic acid (18:1), %	26.4	57.4
Linoleic acid (18:2), %	51.6	22.3
Linolenic acid (18:3), %	6.8	4.5
Density, kg/m^3	922.5	917
Viscosity, mm^2/s	65.4	39.2
Heating value, MJ/kg	37	37
Flash point, °C	>288	>230

Table 2
Properties of model tar compounds.

Compound	Formula	Molecular weight, g/mole	Melting point, °C	Boiling point, °C
Benzene	C_6H_6	78.11	5.5	80
Toluene	C_7H_8	92.14	−93	110–111
Ethylbenzene	C_8H_{10}	106.17	−95	136