Applied Energy 205 (2017) 802–812

Contents lists available at ScienceDirect

Applied Energy

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

Improvement of tar removal performance of oil scrubber by producing syngas microbubbles

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HIGHLIGHTS

- The feasibility of venturi oil scrubber enhancing the absorption surface was investigated.
- The achievements were implemented in a commercial scale fluidized bed gasifier.
- Up to 97.7% of gravimetric tar was removed by the venturi scrubber.
- 100% of naphthalene and phenol was completely removed.

ARTICLE INFO

Keywords:
Tar removal
Vegetable oil
Venturi scrubber
Bubble breakup
Microbubble

ABSTRACT

This paper investigated the feasibility of a low-cost and highly effective tar removal technique using venturi oil scrubber enhancing the absorption surface area by producing microbubbles for tar removal in biomass pyrolysis/gasification processes. The basic experiment was carried out by utilizing a laboratory-scale fixed bed pyrolyzer, and then the achievements were implemented in a commercial-scale bubbling fluidized bed gasifier. In the laboratory-scale experiment, the absorption surface area was evaluated based on the mean diameter and the yield of microbubbles. The venturi tubes with various throat diameter ratios (0.17, 0.42 and 0.67) and inverter frequencies (40, 50 and 60 Hz) were tested to show that the throat diameter ratio of 0.42 and the inverter frequency of 60 Hz were the optimum conditions. Furthermore, it was found that up to 97.7% of gravimetric tar was removed by the venturi scrubber, while naphthalene and phenol were completely removed, which markedly improved the performance comparing with other conventional scrubbers. The 20-h operation of the commercial-scale gasifier also showed that the gravimetric tar removal efficiency of the venturi scrubber was 87.1% on average and there were no naphthalene and phenol observed at the exit of the venturi scrubber as well. Totally, 99.2% of gravimetric tar was removed by using only physical methods comprised of the following: a series of cyclone, ceramic filter, air cooler, water coolers, venturi scrubber and packed bed adsorber, which achieved the syngas quality requirement for internal combustion engines.

1. Introduction

Biomass pyrolysis or gasification is one of the promising conversion technologies to overcome the global warming issues and the depletion of fossils fuels. Its gaseous products called "syngas" is widely applicable to various applications such as heat and power generation and chemical production. Nevertheless, the main obstacle of the syngas utilization is the blockage and fouling caused by tar in piping systems and downstream components due to condensation and polymerization of tar at the temperature below 350 °C [1]. Especially for preventing breakdown in a gas engine, the tar content in the syngas must be lower than 100 mg/Nm^3, while the tar content in fluidized bed gasifiers (10,000–40,000 mg/Nm^3) is often much higher than the limitation [2,3]. Therefore, it is essential to reduce the tar concentration in order to expand the syngas utilization.

Tar is an organic contaminant composed of aromatic ring hydrocarbons. According to ECN [4], tar is classified into five classes under two main categories namely gravimetric (class 1) and light (class 2–5) tar. Currently, there are two methods to remove tar components [5]. One method is the chemical removal, where tar is destructed or converted to permanent gases or smaller molecules, by employing thermal and catalytic cracking [6,7]. However, these advanced techniques require a very high operation temperature (> 1000 °C) [8,9], modification of a conventional gasifier [10] and an expensive catalyst [11].

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http://dx.doi.org/10.1016/j.apenergy.2017.08.071
Received 30 December 2016; Received in revised form 2 June 2017; Accepted 11 August 2017
0306-2619/

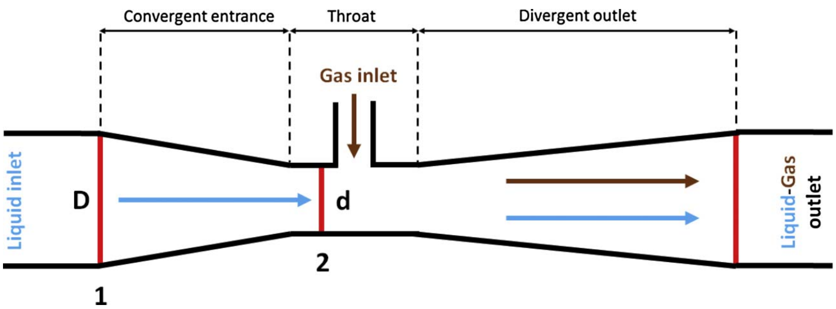

Fig. 1. Illustration of venturi tube.

Thus, the main consideration in this study is the employment of a low cost and highly effective tar removal method. The other method is the physical removal such as scrubbing and so forth, where tar is simply trapped or captured without any chemical reaction [12–16]. The advantages of this technique are the operation of gasifier at a lower temperature specifically at 800 °C, no modification of an existing gasifier, no usage of catalyst, highly effective tar removal and uncomplicated and economical operation in the commercial scale [17]. Therefore, physical tar removal technique has been studied in this paper.

A number of gasification plants generally use water-based scrubber to remove tar and other contaminants. However, previous researches have showed that this removal method resulted in low solubility of gravimetric tar only 31.8% [12]. Regarding the polarity of tar, hydrophobic tar is in large proportion compared to the condensable tar and the hydrophilic tar [15]. Therefore, tar solubility in oil-based scrubbers is much higher than that in water-based scrubbers. Among oily materials, vegetable oil proved to be the most effective absorbent because of its molecular structure. Vegetable oil is composed of fatty acids esterified with glycerol (non-polar tail) containing carboxyl group (−COOH, polar head), while the others are only composed of hydrophobic structures. Thus, vegetable oil is able to dissolve both hydrophobic and hydrophilic tars. The performance of using vegetable oil in various scrubber types on tar removal has been reported. It was found that tar removal efficiency of vegetable oil in packed bed scrubber, which consisted of construction stones, coarse sand and fine sand as bed material, was just 75% [18]. Then, the turbulent mixing effect of the vegetable oil in a bubbling scrubber was investigated and found that the tar removal efficiency is improved with the increase in mixing speed from approximately 65–89.8% [13]. The turbulent mixing exhibited great improvement of tar solubility due to the increase of the absorption surface area. However, tar concentration was still higher than syngas quality requirement for internal combustion engines. Despite the potential to improve the tar removal efficiency by increasing the absorption surface area, no studies were found on this topic. Therefore, it is worth investigating feasibility to improve tar removal efficiency by increasing the absorption surface area. One of the possibility to increase the absorption surface area is to implement in a venturi scrubber, which is able to produce syngas microbubble by bubble breakup mechanism. It was found that tar removal efficiency in downdraft biomass gasifier was up to 80% by water in venturi scrubber [19].

Syngas microbubbles are the syngas bubbles with the diameter range from one to several hundred micrometers, which should significantly increase the absorption surface area compared with the previous study done by employing bubbling scrubbers. Micro-bubbling technique is widely used to improve efficiency in various applications, such as in water treatment process, washing process, plant cultivation and so forth [20–23]. However, to the best of our knowledge, there was no report on the usage of microbubbles for tar removal. Four main techniques can be used in order to produce microbubbles; the bubble breakup [24–26], the ultrasonic wave [27], the microfluidics/MEMS [28] and the pressurized dissolution techniques [29]. This study focused on the bubble breakup technique because the principle of this technique is similar to a venturi scrubber, which has scale up potential. The investigation of microbubble generator, based on air-water mixture, found that the bubble breakup of air increased linearly with an increase of the water flow rate [24]. The venturi type microbubble generator easily generated tiny bubbles of about 100 μm in diameter and the dependence of bubble size distribution on the different liquid flow rates had a favorable effect on the highest water flow rate [25]. An image processing technique was mainly utilized for determining the mean bubble diameter and bubble size distribution [26]. However, previous researches mainly focused on air-water mixture and no studies were found on syngas-oil mixture. The originalities of this study are not only the fundamental study of microbubbles formation of syngas-oil mixture but also investigating effect of syngas microbubbles produced by venturi scrubber on tar removal efficiency, where the relation of syngas microbubble formation to absorption surface area for tar removal did not existed as well.

This study first presents a fundamental investigation on the microbubbles formation utilizing a venturi scrubber. Based on various venturi tube designs, the microbubble size distribution, the mean microbubble diameter, the yield of microbubbles and the absorption surface area were investigated for each condition. Then, the effect of the absorption surface area on the gravimetric and light tar removal performance was investigated in the laboratory-scale experiment. Finally, the venturi scrubber producing syngas microbubbles were demonstrated in a 650 kW_{th} of commercial-scale bubbling fluidized bed gasifier to confirm the utilization of the real applications.

2. Principle of the syngas microbubble formation by venturi scrubber

Fig. 1 illustrates the venturi tube consisting in a convergent, a throat and a divergent part. The pressurized fluid like water or oil is introduced into the convergent part of the venturi tube. According to the conservation of mass and energy, the fluid velocity at the throat position, V_2, becomes higher than the inlet velocity, V_1, while the pressure there, P_2, becomes lower than the inlet pressure, P_1, as shown in Eq. (1).

$$\frac{1}{2}\rho V_1^2 + \rho g Z_1 + P_1 = \frac{1}{2}\rho V_2^2 + \rho g Z_2 + P_2 \tag{1}$$

In this equation, Z_1 and Z_2 are the elevation of the point above a reference plane, which can be neglected, ρ is the density of the fluid and g is the gravity acceleration. Under such a condition of throat position, syngas is able to be sucked into the liquid stream in the lower pressure region of the venturi tube. The sucked syngas is well-broken into numerous microbubbles by the action of a highly-turbulent shear flow called "the bubble breakup mechanism" [24].

3. Experimental setup

3.1. Microbubble size measurement

A schematic diagram of the microbubble size measurement is shown in Fig. 2. According to the opaqueness of the syngas whose microbubble size