INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 16070–16076

Available online at www.sciencedirect.com

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

Managing energy recovered from waste tail gas in a full-scale refinery plant

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
15 September 2015
Accepted 19 September 2015
Available online 26 October 2015

Keywords:
Furnace
Tail gas
Membrane
Grey Correlational Analysis

ABSTRACT

Great savings of fuel consumption and an almost zero-discharge of carbon pollutants can be achieved by the direct reuse of the recovered tail gas as furnace fuel. This paper presents the results of on-site studies using a full-scale furnace to demonstrate the simple adjustments of the furnace operational parameters. The results reveal that when the residual oxygen concentration in the excess air is reduced from 3.6 to 2.4%, the furnace thermal efficiency is raised from 81.9 to 83.2%. Adjusting the furnace damper opening angle from 45 to 39° will lead to annual savings of 1.9×10^6 m^3 natural gas consumption. This paper also presents the use of a membrane separation method to concentrate the hydrogen containing in the tail gas as from 78.7 to 93.9 mol%. The concentrated hydrogen gas is expected to be a valuable material to produce high value added products.

Introduction

Increasing global population, improved living standards, and accelerated economic growth lead to pressing demands for more energy [1,2], thus exhausting the reserve of petrochemical fuel [3–5], increasing the cost of crude oil, and worsening the global warming problems. More enterprises have included sustainable environmental development in their business strategies [6,7] in order to address the mutually correlated issues on environment quality and corporate profits. To maintain continual global economic growth and sustainable environmental development, major industrial nations need to utilize the waste-to-energy technology to produce clean and renewable energy, improve the energy efficiency, and reduce the greenhouse gas emission [4,6,8].

There are many methods that may be adopted by industries to reduce energy consumption and raise energy efficiency. Recovering energy from wastes and developing alternative energy are the major strategies to reduce petroleum fuel consumption and alleviate pollutant emissions [9]. Using recycled wastes as materials to produce final products, or to convert wastes of combustible pollutants into various forms of energy has been practiced by industries [6,10]. For instance, in the waste recycling industry, scrap iron is recycled to reduce the energy demand because producing

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http://dx.doi.org/10.1016/j.ijhydene.2015.09.146

products from original materials is more energy intensive [11]. The steel industry also replaces natural gas (NG) partially with recovered waste blast furnace gas that contains 28% carbon monoxide and 72% nitrogen. This practice can reduce NG consumption, and thus it improves heat recovery rate [12], lowers scrap preheating temperature, and reduces dust emissions [13]. The olive oil industry processes recovered cooking oil using the esterification process to produce biodiesel fuel or low-grade fuel, and uses the products as a regular fuel in the combustion process [14]. In the plastics industry, waste plastic is recycled as either a solid fuel directly or a material to be further liquefied and gasified into fuel to power furnace [15,16]. The tail gas emitted from the petrochemical catalytic reforming, catalytic cracking, the hydrogenation and desulfurization processes of petrochemical plants is recovered and used as alternative fuels to power boilers and furnaces [17].

Nowadays, both developed and developing countries are facing many uncertain, complicate, pressing and mutually correlated energy and environmental issues. Therefore, environmental management problems can no longer be solved alone with unrelated time and space-dependent solutions that are independent of one another [6]. Statistical methods including regression analyses [18–22], time-sequence analyses, artificial intelligence (AI) [18], and fuzzy theoretical analyses [21] may be used to assist in reducing the uncertainty, complication and mutual relationship of environmental management problems. These statistical methods have limitations on application respectively. For example, the regression analysis method is a brief and simple linear model which the accuracy of the predication is not quite satisfactory [18,21,23]; the time-sequence method requires a large quantity of historical data in order to obtain accurate results [24]; the AI analyses depend on training AI models based on the experience accumulated by human experts and historical data [21,25]; the fuzzy theoretical analyses depend on the construction of community functions using in complicate and fuzzy simulation systems, but the operation is more or less subjective and time-consuming [17,21,26]. The Grey Correlation Theory is capable of analyzing uncertain and unclear data and establishing correlations among the data analyzed by predictive models [20,27,28]. This method requires relatively small amount of data, and the predicted results are quite reasonable [15,22]. It has been successfully implemented in the predication, control, and management of economic and social systems, as well as in environmental system decision-making [27].

The present study was carried out using the abundant hydrogen containing in waste gaseous emission from petroleum refining processes as a major source of energy. The concepts of multiple reuses of the recovered energy and management of the wastes are applied by concentrating the hydrogen from the recovered waste gas and by using the recovered waste gas directly as alternative fuel for furnaces and boilers. Specific tasks of this research include: 1) Optimizing the reuse of the recovered waste gas as furnace fuel and 2) Recovering the waste tail gas (FG) is subject to organic membrane treatment to separate the hydrogen gas that can be used as either high quality energy or a raw material for other products. Results in previous on-site studies with full-scale plan operations are obtained by proceeding with systematically changing the operational parameters to achieve maximum furnace thermal efficiencies. Correlations between the control parameters and the responsive performance parameters are then evaluated using the Grey Correlation Analysis method so that a predictive model is constructed to analyze the optimal conditions to operate the furnace using the recovered waste tail gas as the fuel. Hence, the research results will provide practical information on the waste-to-energy technology for industries to implement.

Experimental equipment and methods

Experimental equipment

This research uses two full-scale gas-fired furnaces that provide heat in a currently operating distilling process. Furnace (1) is 4.5 m in inner diameter, 9.5 m in height with 6 sets of burners inside the furnace chamber using gas as the fuel. Furnace (2) has two combustion chambers, and each is 11.4 m in length, 5 m in width and 10 m in height with 14 burners in each chamber (28 burners in total) using fuel oil (FO) and gas as the combined fuel. Fig. 1 shows the schematic diagram of the on-site experimental facility. Both full-scale furnaces are operated using the automatic combustion control system which automatically adjusts the fuel (Furnace (1) adjusts the fuel gas, Furnace (2) adjusts the fuel oil, and the fuel gas is fixed) input flow rate (PC-A and PC-B) to maintain a pre-selected constant temperature of the heated fluid leaving the furnace combustion chamber (temperature indicate control, TIC).

Fig. 2 shows the schematic diagram of the membrane hydrogen separating facility which includes a filtering device and a chamber to house the hollow-fiber membrane made of polyimide. Each module which is 15.24 cm in diameter, and 100 cm in length contains 4000 hollow membrane tubes with 300–450 μm outer diameter and 150–200 μm inner diameter (total permeate area is 40.54 m^2). The 1.27 cm pipeline in diameter and all valves and flow meters are made of 316 stainless steel.

Experimental methods

In the study, the furnace input fuel is controlled automatically by TIC using a series of fuel flow rate control valves to adjust the needed fuel. The fuel control valve is a gate control valve supplied by Fisher Co. The error of which is 0.3% on the full scale. When the TIC drops, the gate control valve opens up to add more fuel until the TIC returns to the pre-selected temperature. The furnace loading is maintained at 100% of the full capacity by keeping a fixed damper angle. The experimental procedures are: 1) replacing the regular furnace fuel, i.e. NG, with the recovered waste tail gas (FG); 2) adjusting residual O_2 concentrations in the flue gas in a range of 4.0–3.0 Vol.%; and 3) adjusting the damper opening angle in a range of 45°–39°. Data were collected 120 min after the adjustments had been made when the furnace operation became steady. The time-averaged composition (in mole fraction) of the tail gas is: