Journal of Cleaner Production 39 (2013) 129–136

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

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

An economic analysis of the continuous ultrasound-assisted oxidative desulfurization process applied to oil recovered from waste tires

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ARTICLE INFO

Article history:
Received 22 April 2011
Received in revised form
13 June 2012
Accepted 3 September 2012
Available online 13 September 2012

Keywords:
Cost–benefit analysis
Energy recovery
Pyrolysis oil
Risk analysis
Ultrasound-assisted oxidative desulfurization process

ABSTRACT

A cost–benefit analysis of the ultrasound-assisted oxidative desulfurization (UAOD) continuous-flow process in organic sulfur removal from pyrolysis oil was carried out. Two separate studies using one and two UAOD units were compared by cost and percentage of sulfur removal. The desulfurization cost for a single UAOD unit was calculated at $0.70/gal with sulfur removal of 68%, whereas the cost and removal percentage were $1.39/gal and 90.91%, respectively, for two UAOD units connected in a series. The monetary value of the health benefits was around $466.59/d for one unit and $623.78/d for two units. Moreover, the best gross income for desulfurized pyrolysis oil after the UAOD system was $1916.46/d in Taiwan. Economic and risk evaluations demonstrated that pyrolysis oil desulfurization using one set of UAOD continuous-flow units can provide full benefits and has few environmental or health impacts.

1. Introduction

As an important aspect of the interaction between nature and society, energy is a major concern for economic development (Platcheck et al., 2008). In the last two decades, the consumption of fossil fuels has markedly increased as a result of the increasing world population and rapid technological development. Unfortunately, the current use of fossil fuels in various sectors for heat and power generation threatens global stability and economic sustainability. To eliminate toxic exhaust and develop sustainable fossil fuel energy, countries around the world have devoted much effort in lowering their energy costs. Recycling and reusing waste energy is essential in achieving this objective (Tsai and Chou, 2004; Tsai, 2010; Könnölä et al., 2007).

About 104,000 tons of waste tires were discarded in Taiwan in 2008; they were either disposed of in a landfill, resulting in fires and air pollution, or left as waste, increasing the demand for space. The disposal of waste tires is a major environmental concern, which led to the reuse of waste tires as an alternative material in many countries (Alan et al., 2012; Cunliffe and Williams, 1998). According to Rodriguez et al. (2001), Dai et al. (2001), and Gonzalez et al. (2001), the heating value of waste tires is around 41–44 MJ kg^{-1}, which makes it an optimal reusable energy. Indeed, many countries have supported research into solid–waste recycling and reuse techniques (Dodds et al., 2009; Stehlik, 2009; Lundie and Peters, 2005), where particular emphasis has been placed on the pyrolysis process for recovering oil from waste tires.

Pyrolysis is the process that converts waste tires into potentially recyclable materials such as flammable gas, pyrolytic oil, and black carbon (Miltner et al., 2010). Recovered oil from pyrolysis contains high concentration of organic chemicals that are of serious environmental concern. In addition, the high concentration of sulfur in

Abbreviations: ASTM, American Society for Testing and Materials; BTs, Benzothiophenes; CBA, cost–benefit Analysis; CPC, Chinese Petroleum Company; DBTs, Dibenzothiophenes; HDS, hydro-desulfurization; HV, heating value; PCTO, passenger car tire oil; TTO, truck tire oil; ODS, oxidative desulfurization; OSCs, organic sulfur compounds; PM, particulate matter; PTA, phase transfer agent; QRA, quantitative risk analysis; RA, risk analysis; Taiwan EPA, Taiwan Environmental Protection Administration; TMC, transitional metal catalyst; Ts, Thiophenes; UAOD, ultrasound assisted oxidative desulfurization; WTA, willingness to accept; WTP, willingness to pay.

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http://dx.doi.org/10.1016/j.jclepro.2012.09.001

pyrolysis oil leads directly to the emission of SO_2 and sulfate particulate matter (PM), which would endanger public health and welfare (Ucar et al., 2005; Palmer et al., 2007). Moreover, organic sulfur compounds (OSCs) in fossil fuels poison catalytic converters, corrode parts of internal combustion engines, and contribute to air pollution. Therefore, in order to extend the lifespan of internal combustion engines and improve the air quality, obtaining a low organic sulfur concentration in recovered oils has become a critical issue around the world. Indeed, hydro-desulfurization (HDS), or distillate hydro-treatment, and oxidative desulfurization (ODS) are two major desulfurization technologies that have been applied recently to industry.

HDS is a large-scale chemical process used to remove sulfur from fossil fuels in industry. However, the high capital and operational costs for HDS have created serious reservations toward recycling wasted energy in small industries. Table 1 summarizes the advantages and disadvantages of different desulfurization technologies. ODS has drawn attention in recent decades due to improvements in the desulfurization efficiency and the reduction of capital and operational costs. Mei et al. (2003) and Wan and Yen (2007, 2008) have demonstrated an innovative desulfurization technology called the ultrasound-assisted oxidative desulfurization (UAOD) process, which combines ultrasound, phase transfer catalysis (PTA), and transition metal catalysts (TMC). The UAOD process can operate at ambient temperatures and atmospheric pressures. OSCs are selectively removed from hydrocarbons by a combination of selective oxidation, solvent extraction, and/or solid adsorption (Etemadi and Yen, 2007a). Thus, the UAOD process is a highly efficient desulfurization method and an environmentally friendly technology that can be scaled up to a portable, modular continuous-flow system (Covert, 2001; Etemadi and Yen, 2007b). Wan and Yen (2008) have illustrated UAOD's feasibility for large-scale operations in relatively small installations with low capital investment and maintenance costs.

Economic analysis, which is always an important consideration for a new technology, can evaluate the viability of UAOD processes in terms of costs and benefits for appropriate technical, social, and environmental applications. A cost–benefit analysis (CBA) can be used to directly measure the overall relationship between the benefit and the cost in terms of money (Sen, 2000) and to provide a comprehensive economic analysis to support decision-making (Ward, 2009). Other economic approaches, including cost-effectiveness analysis, multicriteria analysis, economic growth studies, input–output models, and nonmonetary environmental impact assessments, have more limited scopes.

CBA has been applied to many different projects, such as crop irrigation (Al-Karaki, 1998), surface water treatment regulations (Regli et al., 1999), groundwater quality improvements (Yadav and Wall, 1998), health risks from drinking water (Odom et al., 1999), improvements to sewer systems (Schultz et al., 2004), rainwater harvesting (Ngigi et al., 2005), water reallocations (Messner et al., 2006), biomass-recovered fuel (Petrou and Mihiotis, 2007), and optimal planning of a municipal solid waste management system (Chang et al., 2012). This research illustrates that CBA could be incorporated into an integrated physical, environmental, and economic model to support planning and policy-making decisions related to water resources. The advantages of CBA include transparency and the resulting potential for engendering accountability, the possibility of a framework for consistent data collection, the identification of gaps and uncertainties in the available knowledge, and the use of a metric (money) to aggregate dissimilar effects (such as those on health, visibility, and crops) into one measure of net benefits, environmental conservation, and social welfare.

CBA is an estimation of the benefit from a project during its economic lifetime and the expected cost compared to a certain year (Mishan, 1972; Charles et al., 2002; Graff, 1989; Hansjürgens, 2004, Hu and Lee, 2008). This study used CBA to determine the minimal cost that a person or investor was willing to accept for pyrolysis oil from UAOD technology as an indication of the level of payment required to achieve resource recycling and economic objectives. Three main strategies were evaluated by CBA under the desulfurization processes of pyrolysis oil: (a) one set of UAOD units, (b) two sets of UAOD units connected in a series, and (c) pyrolysis oil without any desulfurization strategy.

The use of UAOD system is often associated with uncertainties because they usually operate in an ever-changing environment where both technical and human factors may contribute to a range of possible accidents. Risk analysis is to provide a mechanism by which decisions concerning the allocation of society's scarce resources can take into account the preferences of those members of society who will be affected by these decisions (Wiek et al., 2008). Naturally, it is important to ensure that these preferences are adequately investigated and carefully considered.

The advancement of science and technology in developed nations improves health and longevity but also continues to present new hazards to the population (Borchardt et al., forthcoming). Many efforts have been directed toward the identification and estimation of the monetary values of safety. These values can be used to quantify the benefits of a proposed safety

Table 1
Comparison of different desulfurization technologies.

	Hydro-desulfurization	Bio-desulfurization	Oxidative desulfurization(UAOD)
Operational conditions	➢ Operates under high H_2 pressure (100–500 psi) and temperature (300–400 °C).	➢ Operates under mild temperature and pressure.	➢ Operates under mild temperature and pressure.
Advantages	➢ Removal of sulfur & nitrogen removal to less than 10 ppm ➢ Complete metal compound removal ➢ Reduction in corrosion of process equipment ➢ Easy treatment process of waste water	➢ Low capital and operational costs ➢ Less greenhouse gas emissions (Linguist and Pacheco, 1999; Mastral., 2000).	➢ High sulfur to sulfone conversion ➢ Shorter reaction time ➢ No hazardous chemicals and byproducts ➢ Catalysts could be regenerated and reused.
Disadvantages	➢ Longer residence time ➢ Spent catalyst becomes a solid waste disposal issue; CO_2 emissions	➢ Technology is not yet applied in the commercial scale. ➢ Unstable desulfurization reaction. ➢ Long operation time.	➢ ODS cannot process and remove thiopene.
Economical benefits	➢ Higher activity using a commercial catalyst	➢ Lower operation cost and production of valuable byproducts. ➢ Production of lower-sulfur fuels.	➢ Upgrade off-road pyrolysis oil to higher value heavy oil ➢ Better refining economics ➢ Ability to optimize crude oil cost
Desulfurization cost	➢ $0.51/gal for deep desulfurization cost.	➢ Lower capital cost of 50% and 15–25% lower operating costs than HDS	➢ $0.7117–$1.4718/gal