Fuel 219 (2018) 364–374

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Study on the integration of fluid catalytic cracking unit in refinery with solvent-based carbon capture through process simulation

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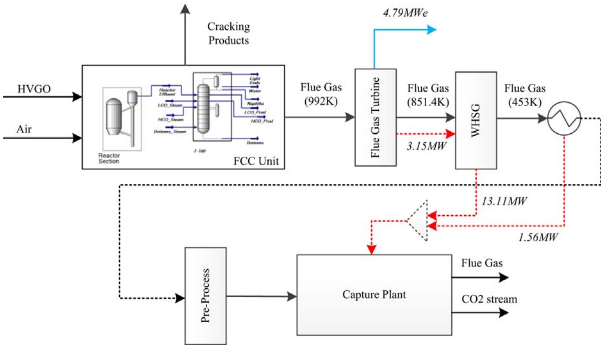
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Refinery
FCCU
Solvent-based carbon capture
Process simulation
Scale-up
Process analysis

ABSTRACT

Fluid catalytic cracking unit (FCCU) is an important refinery process by cracking heavy hydrocarbons to form lighter valuable products, including gasoline and diesel oil. However, the FCCU also generates the largest amount of CO_2 emissions among all the refinery units. To solve this problem, solvent-based carbon capture can be introduced to capture CO_2 in the flue gas from FCCU, but the energy consumption from the reboiler of the carbon capture plant will undoubtedly reduce the economic benefits of the refinery. In this paper, solvent-based carbon capture for an FCCU in a real life refinery is studied through process simulation. This study takes into account the process design and heat integration. An industrial FCCU with a feed capacity of over 1.4 million tons vacuum gas oil per year was modelled, and the process model was validated according to industrial operating data. A carbon capture plant model with MEA solvent was also developed in Aspen Plus® at pilot scale, and scaled up to match the capacity of the FCC unit. Case studies were performed to analyze the integration of the FCCU with commercial scale carbon capture plant, in which different heat integration options were discussed to reduce the energy consumption. The simulation results indicated that a proper design of heat integration will significantly reduce the energy consumption when the carbon capture plant is integrated with an industrial FCCU.

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https://doi.org/10.1016/j.fuel.2018.01.066
Received 3 December 2017; Received in revised form 15 January 2018; Accepted 17 January 2018

1. Introduction

1.1. Background

The emissions of CO_2, known as one of major greenhouse gases, has a significant impact on the global warming and climate change. As a result of the world industry development, CO_2 emissions keep increasing rapidly in the last two centuries. It is reported that if no action is taken to reduce the atmospheric concentration of CO_2, it will rise to above 750 (*ppmv*) by 2100 [1]. As a response, the intergovernmental Panel on Climate Change (IPCC) indicated that CO_2 emissions need to be cut by a minimum of 50% to limit the average global temperature increment to 2 °C in 2050 [2–4].

Fluid catalytic cracking unit (FCCU), known as the heart of the refinery by cracking heavy hydrocarbons to form lighter valuable products, on the other hand, generates the largest amount of CO_2 emissions among all the refinery units, about 20–30% of total CO_2 emissions from a typical refinery [5]. Therefore, capturing CO_2 from FCCU flue gas will be an important step in reducing the total CO_2 emissions from the refinery.

In an industrial FCCU, most CO_2 is released from its regenerator, which is a coke combustion process. Therefore, several carbon capture technologies such as oxy-firing, pre-combustion and post-combustion carbon capture, could be applied to abate the CO_2 emissions [6]. Among them, the solvent-based post-combustion carbon capture (PCC), which commonly uses monoethanolamine (MEA) as the solvent, is the most promising and mature one. Compared with other technologies, it requires minimal modifications to FCCU, and has the most implementation cases in industry [7,8]. Therefore, the solvent-based carbon capture with MEA is applied in this research.

1.2. Previous research

Solvent-based carbon capture has been studied by many researchers. Lawal et al. and Zhang et al. proposed rigorous plant models respectively, and validated the models according to operating data from pilot plants [9,10]. Lawal et al. also analyzed different modelling methods, which showed that rate-based modelling for PCC process is more accurate than equilibrium-based model [11,12]. Considering the high heat duty in the reboiler of PCC stripper will bring a significate energy penalty for commercial implementation, Wang et al. indicated that the energy consumption can be reduced by better process integration [6]. Liu et al. simulated the heat integration of a 600MW_e supercritical coal-fired power plant (CFPP) with PCC process, and several integration cases were analyzed accounting for energy from different positions of the CFPP [13]. Roberto et al. deployed a commercial scale carbon capture plant for a 250 MW_e combined cycle gas turbine (CCGT) power plant, and proposed exhaust gas recirculation to reduce penalty on thermal efficiency [14]. Luo et al. firstly studied on applying solvent-based carbon capture for cargo ships, and the cost degrees for the deployment were evaluated in different integration options [15].

The FCCU has also been widely investigated [16–19]. For the modeling of reaction kinetics, several methods were proposed by classifying the kinetics into different chemical lumps [20–23]. Among them, Aspen HYSYS®, a commonly used chemical engineering software, has also developed a 21-lump model to address heavier and more aromatic feeds [24,25]. Flue gas from FCCU was analyzed by Fernandes et al. in detail, which indicated that the flue gas from FCCU regenerator contained a higher CO_2 concentration compared with flue gas from power plants [26]. In industry, considering the fact that the temperature of flue gas released from the FCCU regenerator is quite high (usually over 900 K), waste heat recovery is therefore an effective way to promote the economic benefits. In this area, Johansson et al. analyzed the excess heat in the view of a whole refinery [27]. Al-Riyami et al. discussed the heat integration of a heat exchanger network for the FCC plant, in which the energy efficiency and economic benefits were taken into account for estimating different heat integration options [28].

For the integration of FCCU with carbon capture plant, de Mello et al. deployed oxy-combustion technology for FCCU in large pilot scale to reduce CO_2 emissions [29]. Furthermore, de Mello et al. also compared the CO_2 capture performance between oxy-firing technology and solvent-based carbon capture for the FCCU at pilot scale, and concluded that oxy-firing concept would be an adequate technology for FCCU if ignoring the total capital cost and consequently FCCU modifications [30].

1.3. Motivation and novel contributions of this work

From the previous studies reviewed in Section 1.2, it can be observed that the deployments of solvent-based carbon capture plant have been mainly focused on the power plants. To the best of our knowledge, few papers studied the integration of solvent-based carbon capture with FCCU for the industrial scale. Flue gas from an industrial FCCU, different from that in power plants, contains more CO_2 and O_2 so that the size of capture plant should be redesign to meet these requirements. Furthermore, considering the large amount of excess heat in FCCU, heat integration should also be analyzed to compensate the energy penalty from carbon capture plants.

In summary, considering the mentioned problems, the novel contributions of this research are listed as follow:

(1) A steady state model for FCCU is developed, the parameters of which are calibrated based on operating data from real industry;
(2) Detailed study on scale-up of the solvent-based carbon capture process is discussed to match the flue gas requirements of the industrial FCCU;
(3) Case studies are performed to compare the performance of deploying solvent-based carbon capture for FCCU with different heat integration options (in order to reduce energy consumption used for carbon capture).

1.4. Outline of this paper

This paper is organized as follows: the model development of the industrial FCCU is introduced and the model is also validated in Section 2. Section 3 describes the model development of the solvent-based carbon capture plant. In Section 4, the process model integration is presented, including flue gas pre-processing, model interface, and scale-up of the capture plant model. In Section 5, two case studies are performed to test the performance of the carbon capture deployment. Conclusions were drawn in Section 6.

2. Model development of the FCCU

2.1. FCCU process description

The reference plant selected in this work is an industrial UOP FCC unit in a Sinopec oil refinery with a feed capacity of over 1.4 million tons vacuum gas oil (VGO) per year. The unit has two major components: riser and regenerator. The simplified flow diagram of the FCCU is illustrated in Fig. 1.

As presented in Fig. 1, the riser is the main reactor where most cracking reactions occur. As all the reactions are endothermic, the feedstock, before entering the riser, should be preheated to around 533–644 K by the feed preheat system. The preheated feed then comes in contact with a hot fluidized catalyst (over 811 K) in the riser, and the components of the feed undergo several reactions on the catalyst surface. After that, the effluent from the riser is sent to the fractionator for the separation of liquid and the gaseous products.

The spent catalyst, on the other hand, is sent to the regenerator,