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Integration of torrefaction in CHP plants – A case study

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ABSTRACT

Torrefied biomass shows characteristics that resemble those of coal. Therefore, torrefied biomass can be co-combusted with coal in existing coal mills and burners. This paper presents simulation results of a case study where a torrefaction reactor was integrated in an existing combined heat and power plant and sized to replace 25%, 50%, 75% or 100% of the fossil coal in one of the boilers. The simulations show that a torrefaction reactor can be integrated with existing plants without compromising heat or electricity production. Economic and sensitivity analysis show that the additional cost for integrating a torrefaction reactor is low which means that with an emission allowance cost of 37 €/ton CO_2, the proposed integrated system can be profitable and use 100% renewable fuels. The development of subsidies will affect the process economy. The determinant parameters are electricity and fuel prices.

1. Introduction

The awareness of climate change has led to the 20–20–20 climate policy in the European Union [1], which refers to a 20% reduction of greenhouse gas emissions compared to the levels of 1990, 20% less primary energy consumption relative to business as usual (BAU) and 20% renewable portion in the final energy use by the year 2020. Furthermore, the Swedish government has set more ambitious goals of 50% renewable energy in final consumption, 40% reduction of greenhouse gas emissions in the sector that is not covered by emissions trading, and 20% reduction in energy intencity compared to 2008 until 2020 [2]. In order to still meet our energy demands from climate neutral resources, it is necessary to transit towards renewable energy systems. Biomass will be playing an important role in the future energy system. Biomass, if grown sustainable, is an endless resource which can be converted into energy by thermal, chemical, thermo-chemical and biochemical methods. Although biomass is presented as a neutral climate impact fuel that can contribute to reduce emissions, it is a problematic fuel due to its high moisture content, low energy content, tenacious structure and low hydrophobicity. These problems may be overcome to make biomass competitive with fossil fuels [3]. Recently, pretreatment technologies to improve the combustion or to develop added value products from biomass like gasification and torrefaction have arisen. Several technologies for biomass utilization have been developed throughout the years. However, combustion is the most common and exploited one [4].

Combustion of biomass is mainly used for heat production in small scale plants for district heating (DH) or combined heat and power (CHP). Strong environmental policies in Sweden are changing the CHP production trends, encouraging the conversion to 100% biomass fuel boilers. About 50% of the heat demand in Sweden is covered by DH [5]. Many of the DH plants are CHP plants, some of which have been converted to biomass firing. Availability and increasing use of biomass have led to a competition of biomass as fuel and raw material. This promotes the use of biomass in optimal ways, both economically and technically.

Direct co-combustion of biomass with coal in pulverized coal-fired boilers is a common practice that can result in economic benefits, improved efficiency and emission reduction, disregarding deposit formation in the boiler [6,7]. However, technical challenges related to feedstock feeding and blending have led to low co-combustion ratios in a commercial scale [8,9]. Savolainen [9] investigated co-combustion ratios of 2.5–8% in fuel energy input for example. Recently, pretreatment technologies to improve co-combustion of biomass have arisen. Torrefaction is a thermal pretreatment method that overcomes the problematic characteristic of biomass and leads to an improved fuel. Torrefied biomass has shown similar characteristics as coal. When biomass is co-fired with coal, torrefaction is recommended as it transforms biomass into a more coal-like product [10]. The advantages of integration of torrefaction are also highlighted by Clausen [11].

Research in torrefaction has mainly focused on the kinetics during torrefaction or the characteristics of the torrefied biomass as van der Stelt et al. [12] indicate. As shown in Li et al. [13] and Asadula et al. [14] it has been proven that biomass can acquire certain resemblance to coal regarding grindability and energy content by

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means of torrefaction. It was also shown that coal can be replaced with torrefied material directly in existing coal mills and burners. However, the torrefied material will not have exactly the same properties as coal. This will affect the flue gas composition and volumes in the boiler, depending on what share of co-combustion is selected. The ash composition of the fuel mix with co-combustion is likely to also cause fouling and/or corrosion on heat transfer surfaces in the boiler. Corrosion in biomass-fired boilers is well documented in for example Sandberg et al. [15]. Further research on corrosion from torrefaction fuels should be carried out to ensure that higher co-combustion ratios are possible. In the study presented by Peduzzi et al. [16] it is shown that the chlorine, nitrogen and sulfur content of biomass is decreased during torrefaction, resulting in low risk for corrosion of the torrefaction product. Erosion hazards can also be avoided in boilers by subjecting the raw biomass to torrefaction [17]. However, little attention has been paid to the system integration of torrefaction which is essential in order to investigate the applicability and feasibility of torrefaction from a system perspective [18]. Integration of torrefaction has been studied by Kohl et al. [19] where the temperature and residence time were not studied in detail as well as in terms of the composition of torrefaction gases.

Larger flue gas volumes will affect the heat transfer in the boiler and therefore it is necessary to investigate how the plant will react to (i) the integrated torrefaction reactor with an existing CHP plant and heat demand, and (ii) how co-combustion of torrefied wood will affect the plant performance.

This paper presents findings of the integration of a torrefaction reactor with an existing CHP plant. The integration aims to replace part of the remaining fossil fuel feedstock with torrefied biofuel at the same time that the system performance is not compromised. Simulation models are setup and validated separately before integrated to find the efficiency and economic features of the proposed system. Different integration alternatives are assessed in this study including integration in the flue gas side and integration in the steam cycle. After considering the technical and economic factors a sensitivity analysis is carried out. The results focus on the efficiency and economy for an integrated torrefaction reactor compared to a reference CHP plant.

2. Integrating torrefaction in CHP

Torrefaction is a pretreatment method for biomass gasification and for using biomass to replace fossil fuels in coal-fired power plants, which can overcome the disadvantages of biomass as fuel, such as low energy density, high moisture content and low friability. Torrefaction is conducted under inert conditions and atmospheric pressure at temperatures between 200 °C and 300 °C [12]. The mass loss occurs due to devolatilization, but most of the energy content in the raw biomass is kept in the torrefied product. The energy content in the produced torrefaction gases has to be utilized for efficiency purposes [18]. Compared to raw biomass, the torrefaction product has the following advantages: increased hydrophobicity, increased energy density, more homogeneous final product, improved grindability and lower O/C ratio [12].

Although the principles of torrefaction are known since the 1930s, very few commercial processes is available on the market. Many experimental studies of torrefaction of different biomass are presented in the literature. Torrefaction has been proven on laboratory and pilot scale but there are still some challenges to overcome in order for this technique to become commercial. The torrefaction product can be used in large scale power production, industrial and residential heating and for chemicals production via gasification. Not only the operational parameters like residence time and torrefaction temperature need to be optimized, but the standardization of the outcoming product requires focus in order to establish the market for torrefaction. The torrefaction product is usually referred to as biocoal due to its resemblance to coal.

The energy requirements of a torrefaction system are commonly considered to reach autothermal operation where the energy content in the torrefaction gases are combusted to supply heat to the torrefaction reactor and dryer [20]. However, varying moisture content and feedstock compositions results in changes in the gas volume and composition, which results in variation of energy supply to the reactor. Consequently, the quality of the torrefied product could be risked [21]. The amounts of gas released which could be used for heating of the reactor varies and does not always equal the required heat. If heat is supplied externally during more stable conditions and the torrefaction gases are utilized elsewhere, this can be overcome.

3. Modeling and simulation

A case study of a CHP plant in Västerås, Sweden has been selected to perform the evaluation. Västerås is Swedeńs 6th largest city with 140,000 inhabitants and it has one of the largest CHP plants in Sweden. The plant consists of 5 boilers, where boiler 1 and 2 (B1 and B2) were converted from oil firing to coal and later to tall oil pitch and are now serving as topping or backup boilers with very short operating time each year. Boiler 3 is oil fired and functions as a power reserve and only operated when there is a shortage of electricity. Boiler 4 (B4) is fired with coal and peat and boiler 5 (B5) with biomass. B5 is operated about 8000 h per year and B4 about 5000 h per year. They are connected to a joint turbine system and thus produce electricity in the same generator. District heating is also produced to supply the city with the required heat demand.

The studied concept is schematically displayed in Fig. 1 and focuses on B4 and B5. Torrefaction gases are led back to the boiler and co-combusted to give some additional energy to the boiler. The torrefied product can be used directly or stored without changing its properties, for example increasing in moisture content. Two integration configurations have been studied; one where flue gas is used in a heat exchanger to heat the torrefaction reactor and one where superheated steam is used. The heating source is not in contact with the torrefied material and the heating media passes on the surface of the torrefaction reactor, which is considered to be a screw conveyor reactor.

Within a steam based CHP plant, the possibilities of integration opportunities are limited due to the temperature requirements of torrefaction, 200 to 300 degrees. On the flue gas side, the temperatures are stable even if the plant is operated at part load. Air preheating after the economizers in the boiler is usually working in suitable temperatures for torrefaction.

In the steam cycle, temperature levels are usually lower than required throughout the low- and intermediate pressure turbine expansion. Utilization of live-steam from the boiler (500–600 °C), or high pressure steam after expansion in the high pressure (HP) turbine (300–400 °C) therefore has to be used for integration purposes. The steam is usually still in the superheated region after the HP turbine which opens up the possibility for an integration approach to use steam at high temperatures for de-superheating to reach the required temperatures.

The integration of a torrefaction unit means in terms of energy that the torrefaction unit has to be large enough to be economically viable and be able to torrefy enough fuel to have a large impact on the replaced fossil fuel to the boiler. On the other hand, the torrefaction unit should not have such energy demands that it gives a negative effect on the boiler performance or economic impact in terms of electricity and heat production. Heat supplied to the DH network cannot be compromised. Here, we consider two different integration alternatives and compare them to each