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System integration study of oxy-biosyngas combustion based metal heating process using Aspen Plus

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ABSTRACT

Given the increasing concerns on emissions, efficient and environmentally friendly combustion technologies are urgently needed to address energy trilemma. Metal heating is a large component of energy-intensive processes, as its energy consumption accounts for one third of the steel manufacturing process. Early attempts at using a new flameless oxy-fuel combustion burner give high performance, low NOx, and low-cost heating for the steel industry, while biosyngas is considered as an alternative fuel for reheating furnace with aiming at CO_2 mitigation. Yet, all these technical solutions are developed in isolation. This paper investigates the system integration of biosyngas production, air separation unit (ASU), reheating furnace and heat recovery (HR) steam cycle, in order to enhance energy efficiency of steel industry and enable so-called negative emissions. An integrated system model was developed using Aspen Plus to evaluate the feasibility of the proposed integration from the perspective of heat and mass balance. In particular, to study the impacts of fuel switching on the heating quality of the furnace, a three-dimensional furnace model considering detailed heat transfer processes was embedded into the system. The simulation results show that the proposed system integration strategy is technically feasible. The electricity generation of the HR steam cycle used can compensate for about 90% of ASU's energy consumption. The system is carbon capture-ready for being further integrated with CO_2 conditioning and transportation processes.

Keywords: metal heating process, biosyngas production, oxy-fuel combustion, air separation unit, heat recovery

1. INTRODUCTION

Combustion will still play a major role in human energy use for a long time to come. In fact, despite human beings' continuous commitment to the development and utilisation of new energy sources in recent years, human energy consumption is still mainly obtained through combustion, and emissions from the combustion process are also the main cause of environmental pollution. Global issues such as the greenhouse effect and ozone hole have become the focus of attention and research of people all over the world [1]. With the increasing scarcity of non-renewable resources such as oil, natural gas, and coal, engineers are committed to the development of various high-efficiency, low-pollution combustion technologies around the practical issues of how to improve resource utilisation and minimize environmental pollution. Advanced combustion technologies and renewable resources utilisation have emerged at the historic moment and have shown broad development prospects.

The reheating furnace is an indispensable thermal equipment in the steel production process. It heats intermediate steel products such as slabs, billets or blooms (known as stock) uniformly according to the production rhythm, so that the surface temperature and internal temperature distribution of the stock meet the rolling requirements. According to practice figures, the energy consumption of the reheating furnace accounts

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for about 70% of the rolling process and 15-20% of the total energy consumed [2-3], which directly affects the production cost of the steel industry. The energy-saving technological retrofitting and optimal integration of the reheating furnace are of great significance for achieving sustainable steel production.

With oxygen becoming more affordable in cost and more efficient in productivity, oxy-fuel combustion technology has received much attention in steel-making plants, particularly for reheating and annealing processes. Our previous work [4] studied the impact of flameless oxy-fuel (propane) combustion on the thermal performance of a pilot-scale steel reheating furnace. Compared to air-fuel combustion, the results of oxy-fuel combustion indicated a marked improvement in the furnace specific fuel consumption (approximately 16%), due to the enhanced radiative properties of the furnace atmosphere and reduced exhaust energy losses as the result of less dilution effect from nitrogen. However, this research raised another concern about the additional energy consumption associated with oxygen production.

On the other hand, in recent years biomass as substitution of fossil fuels and reducing the need for coke based reductant agents has been considered as one of the ways the iron and steel industry can achieve its goals of reducing CO_2 emissions in the short to medium term [5]. However, biosyngas typically has a low energy density and a high gas emissivity of the product of combustion, this might limit its use in high temperature processes. To address this concern, we conducted a feasibility study of the reheating process using biosyngas as fuel [6]. The results show that biosyngas is suitable for direct use as fuel for reheating furnaces and its combustion can meet the heat transfer requirements of the reheating process. Should CO_2 capture be considered, it has a potential to achieve the capture without external energy input which results in so-called negative emissions of CO_2 [7].

In this study, we explored the system integration of oxygen and biosynthesis production and metal heating processes, i.e. oxy-biosyngas combustion based metal heating process, while considering the heat recovery CHP cycle to improve the overall system efficiency.

2. SYSTEM INTEGRATION

As shown in Figure 1, first the raw biomass enters the fluidised bed gasifier (steam/biomass of 1 and carbon conversion of 0.9 assumed) and undergoes processes such as drying, pyrolysis, and gasification in sequence. A heat recovery (HR) steam cycle is integrated into the system to recover the condensation heat of the raw biosyngas and the high-grade waste heat from the flue gas (heating it to saturated and superheated state @135bar/470°C). The motive steam generated by the steam cycle drives the generator to generate electricity supplying air separation unit (ASU, 95%O2 assumed) while the steam exhaust is used as the gasification agent of the gasification process. Most of the oxygen produced by ASU is supplied to the reheating furnace for oxy-fuel (biosyngas) combustion, while a small portion is used to supply the fluidised bed gasifier.

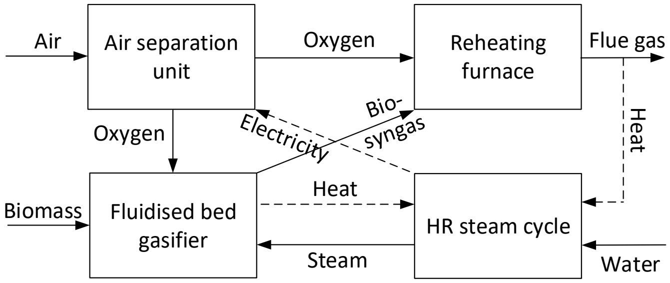

Figure 1. A schematic diagram of system integration

The reheating furnace hypothesised in this study is a pilot-scale reheating furnace located at Swerim AB, Sweden [4], with a production capacity of 3 tonne/hr and a target heating temperature of 1250°C (see Figure 2). All other parameters of the fluidized bed gasifier and HR steam cycle are set to ensure normal operation of the reheating furnace. Table 1 lists the proximate and ultimate analyses of the raw biomass.

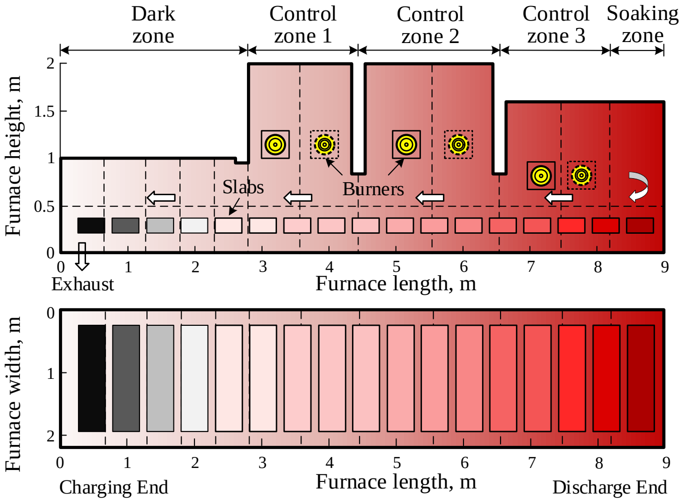

Figure 2. Outline of the pilot-scale reheating furnace

3. SYSTEM MODEL DEVELOPMENT

Steady state operation of the proposed system integration has been implemented using Aspen Plus^{TM} commercial simulation software. The process flowsheet designed (see Figure 3) can be used to calculate the mass and energy balances of four main processes: biosyngas production, air separation, reheating process and HR steam cycle, and their integration in terms of heat recovery and reuse.

Table 1. Proximate & ultimate analyses of raw biomass [8]

Moisture content (wt%)	8
Proximate analysis (wt%, dry basis)	
Volatile matter	82.29
Fixed carbon	17.16
Ash	0.55
Ultimate analysis (wt%, dry basis)	
C	50.54
H	7.8
O	41.11
N	0.15
S	0.57
Average particle size (mm)	0.25-0.75
Char density (kg/m^3)	1300

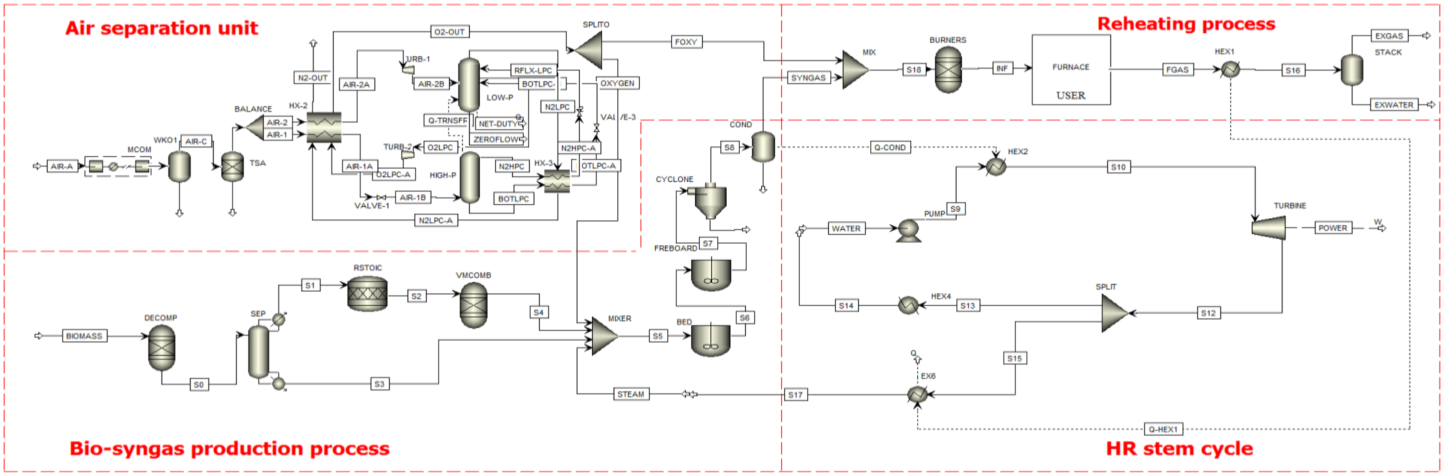

Figure 3. Process flowsheet developed using Aspen Plus

The previous work of *Hu et al.* [9-10] had described the implementation of Aspen Plus modules for ASU and fluidized bed modelling, respectively, in detail which will not to be repeated here. It should be noted that the reaction kinetics were necessarily updated to accommodate the gasification processes such as pyrolysis, volatile matter combustion, and bio-char steam gasification in this study. In order to particularly study the impacts of fuel switching and combustion improvement on the heating quality of the furnace while evaluating the energy efficiency of the entire system, a three-dimensional furnace model considering detailed heat transfer processes was developed [11] and embedded into the system through an Aspen Plus user defined model. In the simulation, the furnace model can calculate the slab heating profile and the furnace temperature distribution based on the retrieved zero-dimensional stream data from the upstream and then pass the stream data of the flue gas to the downstream. It should also be noted, the emissivity - pressure multiplying beam length (ε-pL) data at different temperature and stoichiometric amount of oxidant were necessarily updated to cover the operating conditions of oxy-fuel combustion [4]. A simple steam cycle was employed to evaluate whether the electricity generated by the waste heat can meet the load demand of the air compressors (the main source of ASU load).

4. RESULTS AND DISCUSSION

Table 2 lists the system simulation input parameters and key results under difference combustion environments. The biosyngas production process in different systems operate under the same conditions. In general, the biosyngas produced has close net heating value and composition, in which carbon monoxide and hydrogen in sum account for more than 80%.

Table 2. Key input parameters and results of the system simulations

<u>*Input parameters*</u>	Air-biosyngas [6]	Oxy-biosyngas
Biomass input, kg/hr	258	241
Excess air/O_2, mol%	10.0	3.0
Motive steam, bar/°C	135/470	135/470
Stack inlet temperature, °C	100	100
<u>*Results*</u>		
Gasification temperature, °C	850	845
Biosyngas composition, mol%		
O_2	0.273	0.251
CO	33.20	33.00
H_2	50.06	49.89
CO_2	9.240	9.168
H_2O	7.130	7.131
Biosyngas heating value, MJ/kg	13.60	13.58
Turbine generation, kW	117[1]	75
Flue gas temperature, °C	487	250
Flue gas flow rate, kg/hr	1872	650
ASU energy consumption, kW	N/A	85
CO_2 concentration in flue gas, %mol	16.7	83.5

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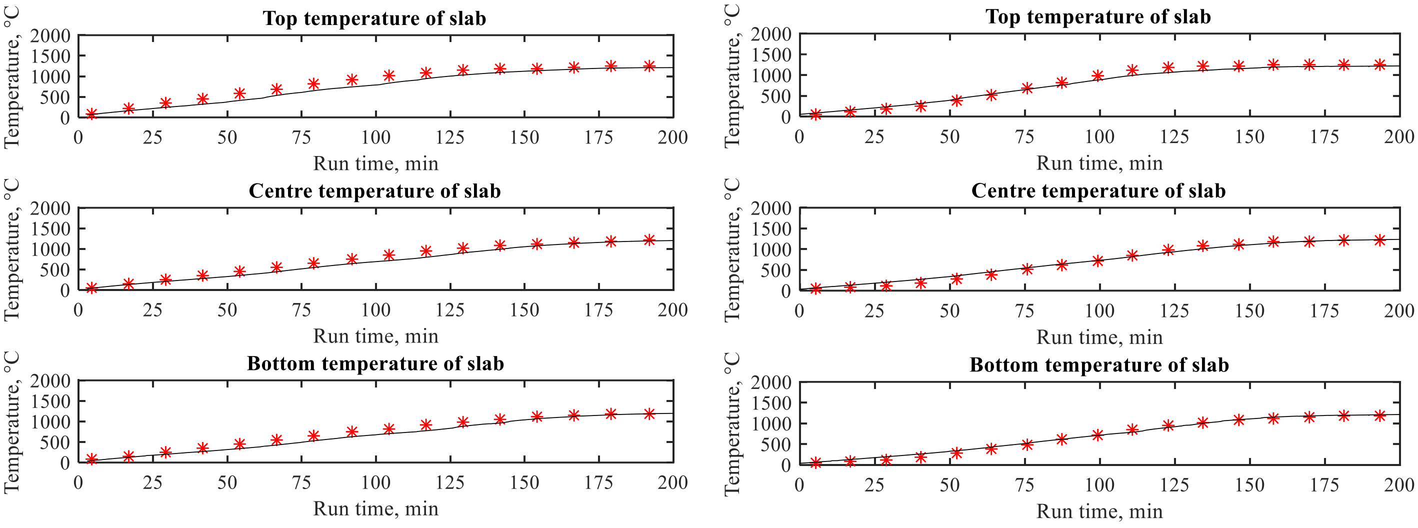
[1] Erratum to [6], turbine generation of 390kW in Table 2 should be 117kW.

By recovering the condensation heat of the raw biosyngas and the waste heat from the flue gas, the motive steam in the waste heat recovery process of the two systems can generate 117kW and 75kW of electrical energy, respectively. This difference is attributed to the low flue gas temperature of the reheating furnace in the case of oxy-biosyngas combustion, together with a significant low flow rate making it incompatible with HR steam cycle. However, the ASU in the oxy-biosyngas combustion system requires an additional 85kW of electricity to produce oxygen, equivalent to 864kW/kgO_2. This implies that the electricity generation of the HR steam cycle operating at current steam parameters cannot fully compensate for the energy consumption of ASU, unless a higher efficient thermal cycle is used. It should be noted that two combustion systems have very different CO_2 concentration in flue gas. Actually, this is the main feature of oxygen-enriched combustion, which will significantly reduce the cost of subsequent CO_2 capture compared to the post-combustion capture technology [12]. However, the energy consumption of ASU should not be ignored, so the cost of carbon capture by oxyfuel combustion mainly depends on the energy consumption of oxygen production.

The performance of the reheating furnace in the integrated system was further examined using real trial data. It should point out that these data come from trials using other fuels [4], which can be used as a reference to evaluate heating performance of the reheating furnace because the desired heating curve only depends on designed operating conditions under steady-state. Figure 4 shows the comparison of the predicted top, centre, and bottom temperature profiles of the slab to the desired heating profile under different combustion environments. As can be seen from this figure, in general, the predictions were in good agreement with the desired heating profile. However, slight under-prediction is still



(a) Air-biosyngas [6]

(b) Oxy-biosyngas

Figure 4. Comparison of the predicted slab heating profile with the desired heating profile (red symbol: predicted profile; black line: desired profile)

Table 3. Simulation comparison of furnace energy balance by air-fuel combustion and oxy-fuel combustion

		Energy input		Energy output			Performance			
	Units	Q_f	$Q_{o/a}$	Q_s	Q_e	Q_l	E_c	E_f	*SFC*	*Cap.*
Oxy-	MW	1.151	0.005	1.047	0.044	0.083	96.60	90.91	0.987	4.198
biosyngas	%Q_f	100.0	0.442	90.90	3.840	7.171				
Air-	MW	1.319	0.052	0.988	0.297	0.085	81.43	74.95	1.203	3.946
biosyngas	%Q_f	100.0	3.969	74.95	22.54	6.458				

Q_f, fuel energy input.
$Q_{o/a}$, preheated oxygen or air energy input
Q_s, energy transferred to steel slabs.
Q_e, energy in exhaust gases as they leave the furnace.
Q_l, energy losses to furnace walls.
E_c, combustion efficiency, $1+(Q_{o/a}/Q_f)-(Q_e/Q_f)$ as a percentage.
E_f, furnace efficiency, Q_s/Q_f as a percentage.
SFC, specific fuel consumption, Q_f/tonnes, usually expressed in GJ tonne^{-1}.
Cap., heating capacity in tonne hr^{-1}.

observed around the dark zone in the case of oxy-biosyngas combustion. This is believed to be due to the fact that to maintain the same heat transfer to the slabs, a smaller firing rate is required in the oxy-biosyngas combustion system compared to the air-biosyngas combustion system, and this typically results in a drop in the flue gas temperature and a reduced mass flow rate.

The cumulative thermal energy both entering and leaving the furnace are shown in Table 3. The oxy-biosyngas case has a significantly smaller oxygen energy input ($Q_{o/a}$) and exhaust energy loss (Q_e) due to mainly the absence of nitrogen in the combustion along with lower flue gas temperature. As a result, the furnace efficiency is substantially improved by about 16%. The specific fuel consumption and heating capacity have therefore dropped correspondingly.

5. CONCLUSIONS

In this paper, system integration of oxygen production (cryogenic air separation), biosyngas production, reheating furnace, and heat recovery steam cycle is proposed and proved through mass and heat balance. Particularly, real trial data is used to examine the performance of reheating furnace to ensure heating quality. The results show that the proposed system is technically feasible, and the reheating furnace can work well to heat the slab to the target temperature. The efficiency of biosyngas fuelled furnace can be improved by about 16% in oxygen-enriched combustion environment. About 90% energy consumption of the air separation unit can be compensated by the electricity generation of the heat recovery steam cycle used, and it has the potential to fully compensate by using a higher efficient thermal cycle. Although the proposed system is technically feasible, the optimum operating conditions must be studied to further enhance the system efficiency.

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