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Industrial heat recovery from a steel furnace for the cogeneration of electricity and hydrogen with the copper-chlorine cycle

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ABSTRACT

A novel integrated system for the production of hydrogen at a high pressure utilizing steel furnace waste heat is presented and analyzed in this paper. The system utilizes a hybrid thermochemical copper-chlorine (Cu-Cl) cycle. This study integrates the industrial waste heat source with the thermochemical Cu-Cl cycle combined with a hydrogen compression system. The electrical energy required by the system is provided by a supporting Rankine cycle. The hydrogen compression system compresses hydrogen to a pressure of 750 bars. The integrated system is simulated with Aspen Plus software. Energy and exergy analyses are performed for the integrated system. Results from the simulations are presented and discussed. The overall energy efficiency is 38.2% and overall exergy efficiency is found to be 39.8%.

1. Introduction

Worldwide energy demand is increasing rapidly. A major part of the energy demand is supplied by fossil fuels, which is leading to environmental problems and global warming [1]. Renewable energy systems such as solar energy and hydrogen fuel cells have been increasingly adopted [2]. Also, improving energy efficiency and waste heat recovery are promising means of reducing greenhouse gas emissions. This paper examines waste heat recovery from steel-producing operations for the production of hydrogen as a clean energy carrier.

The World Steel Association reported that steel production for 64 countries in January 2018 is about 139.4 million tonnes and a 0.8% increase is found as compared with January 2017. While in 2017, a 5.3% increase in the steel production was found as compared to 2016.

Steel is a basic component of infrastructure worldwide. Many industries like automobiles, pipelines, appliances, buildings, and bridges use steel as a base material. Steel is produced in furnaces by melting different ores like scrap metal, iron ore or other additives. The molten metal from the furnace is solidified into partially finished shapes before being rolled in different forms like beams, rods, sheets, wire, and tubing [11,3]. In this paper, useful products of hydrogen and power are produced by industrial waste heat or flue gases from a steel plant. Past studies have been presented for waste heat recovery, blast furnace operation, steel heat treatment and waste heat recovery [3–9]. The flue gas temperature from a typical steel plant is 810 °C [10].

Mohammadi and McGowan [11] proposed several integrated configurations for cogeneration and trigeneration of cooling, power and fresh water. A solar tower was integrated to operate a regenerative Rankine cycle including steam extractions and condensation. It was designed in a way to supply the multi-effect distillation and absorption cooling with the required thermal energy. It was concluded that the design utilizing steam extraction with a lower pressure and temperature behaves more efficiently. For cogeneration of fresh water and power, integrating multi-effect distillation and a power cycle using condensation steam was found to be more efficient. Rankine cycles have various advantages like suitability for cogeneration of heating and cooling, wide availability and low frictional losses but one disadvantage is the high-pressure drop.

Arzbaecher et al. [12] examined a range of industrial waste heat recovery methods. Waste heat is the energy associated with different waste streams of heat like exhaust gases leaving the industrial plant [12]. Luo and Feng [13] presented a paper on waste heat recovery from blast furnace slag which is a main by-product of the steel industry. This waste heat from the blast furnace slag goes through an endothermic reaction and produces hydrogen. The effects of different parameters like the mass flow ratio, feed moisture, slag temperature and particle size on the gas characteristics and product were evaluated. It was concluded that the blast furnace slag temperature significantly affected the distribution of pyrolysis products.

Zhang et al. [14] presented a study that showed the energy consumption of the steel industry can be reduced and operations can be made more efficient by making use of waste heat from blast furnace

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Nomenclature

$\dot{En}$	energy rate (kW)
ex	specific exergy (kJ/kg)
$\dot{Ex}$	exergy rate (kW)
$\dot{Ex}_{dest}$	exergy destruction (kW)
ex_{ch}	standard chemical exergy (kJ/kg)
ex_{ph}	standard physical exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
LLV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat (kJ)
$\dot{Q}$	heat rate (kW)
s	specific entropy (kJ/kg K)
$\dot{S}_{gen}$	entropy generation (kW/K)
T	temperature (°C)
$\dot{W}$	power or work rate (kW)

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

0	ambient conditions
B#	block name in Aspen Plus
Cu-Cl	copper-chlorine cycle
i	input
ov	overall
RC	Rankine cycle
W	work
ch	chemical
dest	destruction
en	energy
ex	exergy
ph	physical

Acronyms

CSPA	Canadian Steel Producers Association
Cu-Cl	copper chlorine cycle
HEX	heat exchanger
HPT	high-pressure turbine
HRSG	heat recovery steam generator
LPT	low-pressure turbine
MSRC	multistage reheat Rankine cycle
RC	Rankine cycle

slag. On the basis of dry slag granulation technology, integrating a Brayton cycle was proposed for this waste heat recovery. An air Brayton cycle thermodynamic model was used to analyze the performance of waste heat recovery and it was concluded that 12% recovery efficiency could be achieved. Dal Margo et al. [15] presented a new energy based recovery system by integrating the steel industry waste heat with phase change materials. An auxiliary section was introduced between the steam generators. Fluid flowing inside the tubes extracts the heat from phase change materials by heat transfer. Zhang et al. [16] presented new techniques of heat recovery from molten slag. Quenching water is the most common technique used for heat recovery. Some of the physical heat recovery methods like air blasting, mechanical crushing and chemical heat recovery methods like coal gasification and methane reforming were proposed and investigated.

Adballa et al. [17] presented a review of various methods of hydrogen production, storage, transportation, and applications. Due to the increased energy demand, different methods and sources for producing hydrogen are discussed. Also, renewable resources are considered as one of the most potential candidates for this purpose. Hydrogen mostly exists in a combined form with oxygen as water which covers about 71% of the earth. Moreover, hydrogen can be produced through renewable sources. Hydrogen production through several processes like renewable sources, fossil fuels and biofuels and key challenges being faced by the hydrogen industry were considered and reviewed in this study.

Hydrogen has a clear benefit of working as both an energy carrier and energy storage system [18] in power plants. A plant's efficiency can be increased by operating the power plant at full capacity with excess energy stored in the form of hydrogen [19]. Wang et al. [20] presented a study on a new thermochemical Cu-Cl cycle for producing hydrogen while accompanying the requirements of reduced excess steam. The thermochemical copper-chlorine cycle is considered as one of the promising methods for hydrogen production. The thermal requirements for various steps of Cu-Cl cycles and their design features, heat upgrading and heat transfer were reported in the paper. Naterer [21] presented a study on the second law viability of upgrading waste heat with chemical heat pumps for hydrogen production by the thermochemical Cu-Cl cycle. Low-grade waste heat is upgraded by exposing this heat to very high-temperature exothermic reactors of ammonia/salt through chemical heat pumps. The electricity can be produced by utilizing this partially recovered waste heat by a heat engine, and this electricity is further used to operate compressors to enhance the vapor pressure in the heat pumps. A Second Law analysis and COP results for a heat pump were examined and presented.

Al-Zareer et al. [22] designed a novel hydrogen production system containing a thermochemical copper-chlorine cycle, a water gas shift membrane reactor, a hydrogen compression system, a hydrogen-fueled combined cycle and a cryogenic air separation unit. The generated steam is used to operate the Cu-Cl cycle. An electrolysis reactor in the Cu-Cl cycle is supplied with the power through the Brayton cycle. Hydrogen is then transported to the hydrogen compression system. The overall energy efficiency was calculated as 51.3% and the exergy efficiency was found to be 47.6%.

Orhan et al. [23] presented a study and analyzed various Cu-Cl

Table 1
Four-step Cu-Cu cycle reactions [24].

Step	Name	Reaction	Temperature range (°C)
1	Hydrogen production	$2CuCl(aq) + 2HCl(aq) \rightarrow H_2(g) + 2CuCl_2(aq)$	< 100
2	Drying or crystallization	$CuCl_2(aq) \rightarrow CuCl_2(s)$	< 100
3	Hydrolysis	$2CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g)$	400
4	Oxygen production	$Cu_2OCl_2(s) \rightarrow 0.5O_2(g) + 2CuCl(l)$	500