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Upgrading Waste Heat for Process Heating using a Thermochemical Heat Transformer: A Case Study of the Iron & Steel Industry

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Abstract—The iron and steel industry is one of the largest energy sectors, producing significant amounts of waste heat. This industry has a potential of about 170 TWh per year for producing waste heat. Recovering and upgrading this potential waste heat is essential for improving the energy efficiency of the system and reducing carbon emissions. Different methods, such as the organic Rankine and Kalina cycles, are used to recover this waste heat potential. Also, some innovative techniques exist to upgrade waste heat, like mechanical heat pumps and thermochemical heat transformers (TCHTs). The TCHT systems operate on a reversible chemical reaction cycle, utilizing a suitable thermochemical material (e.g., salt hydrate) that can be operated in a long-term cycle at the target temperature. This study presents the application of a TCHT to upgrade medium-grade waste heat from 230°C to 290°C in the iron and steel industry. The material selected to operate in the TCHT system is $SrBr_2$. H_2O can be operated at temperatures ranging from 150 to 300°C. There are available waste heat streams from ovens and furnaces. These exhaust streams reach temperature values up to 230°C. This available waste heat is transferred to the TCHT system, and after upgrading, the temperature reaches 290°C, which can be utilized in the hydrothermal carbonization process as a process heating application. For the proposed system, the impact of different condenser temperatures is investigated on the coefficient of performance (COPh) of the TCHT system (based on thermal power) and the exergy efficiencies of the system. The results indicate that the COPh of the proposed TCHT system is between 0.6 and 0.62, while the exergy efficiency varies between 85.5% and 89.3% when the condenser temperature is between 35°C and 70°C.

***Keywords*:** Thermochemical heat transformer, Industrial waste heat, Process heating, Heat upgrading, Iron and steel industry.

1. Introduction

Industries worldwide account for approximately 30% of total energy consumption [1]. Most energy consumed in industrial procedures is wasted, mainly as heat, discharged to the environment through exhaust streams, cooling systems, and flue gases. This enormous amount of waste heat provides an excellent opportunity for being recovered and utilized to reduce energy losses and carbon footprints. Among various industries, Iron & Steel produces the most waste heat, estimated at about 170 TWh yearly, because of the high demand for this raw material. Therefore, this sector has enormous potential for energy efficiency improvement by applying waste heat recovery and heat upgrading techniques. Waste heat recovery techniques and heat enhancement in energy-intensive industries such as iron and steel will overcome the above-mentioned global challenges. Industries with the potential for high waste heat (i.e., Iron & Steel) can use these innovative technologies to recover and upgrade this massive amount of waste heat, thereby reducing their overall energy consumption, producing fewer greenhouse gas emissions, and contributing to a more sustainable future.

Widely used waste heat recovery technologies such as organic Rankine cycle (ORC) and Kalina cycle have seen extensive deployments in utilizing low-to medium-grade waste heat. These technologies operate by converting waste heat to mechanical or electrical energy, which is available either for internal reuse in the process or can be fed into the grid. However, the efficiency of such systems remains relatively low, and the temperature operation range is somewhat limited. For instance, ORC systems cannot recover the waste heat efficiently at higher temperature ranges, while complexities in the Kalina systems make their implementation economically viable.

Other classes of waste heat utilization technologies include mechanical heat pumps that upgrade waste heat to higher temperature levels. However, their dependency on electrical energy and operational limitations in high-temperature environments have limited their wide applications in industries with medium and high-grade waste heat streams [2]. In particular, new technologies are required to upgrade waste heat to a temperature level directly usable in industry. This will significantly extend the perspectives toward higher energy efficiency and sustainability.

The limitations of conventional methods indicate the need for innovative technologies capable of overcoming those challenges that concern waste heat recovery. Among alternative technologies, thermochemical heat transformers (TCHTs) have gained attention because these systems can upgrade waste heat to higher temperature levels through reversible chemical reactions. Unlike mechanical heat pumps, TCHTs have no requirement for any external electrical power input; instead, TCHTs use latent energy stored within thermochemical materials. This facilitates more effective heat upgrading, especially with the availability of renewable or intermittent waste heat streams[3]. TCHTs will make waste heat recovery much more viable, particularly in highly energy-consuming industries like iron and steel.

TCHT systems consist of two reactors, which can be operated in two main phases. In the charging phase, heat is supplied to the reactor at a lower temperature (e.g., from industrial waste heat). The thermochemical material absorbs this heat. As a result, the dehydration reaction takes place during an endothermic reaction. The reactor in this phase is called a dehydration reactor. In the discharging mode, the reserve reaction occurs when heat is needed at a higher temperature level. The reaction in this phase is exothermic, and the reactor is called a hydration reactor. At the end of this phase, the chemical reaction releases heat at a high temperature [3]. The configuration of the TCHT systems depends on the reaction types and applications. The solid/gas systems use solid reactants such as salt, metal oxide, etc., while liquid/gas systems use liquid or gas. In this study, we are focusing on the solid/gas TCHT systems [3]. Thermochemical materials are classified based on their working pairs. According to this classification, solid/gas TCHT systems are classified into five main categories, including NH_3 system, SO_2 system, water vapor system, CO_2 system, and H_2 system. Among these working pairs, the NH_3 system [4], [5] and water vapor systems [6] are widely used in the literature.

In the iron and steel industry, there are available waste heat streams coming from ovens and furnaces. These exhaust gas streams reach temperature values up to 230ºC [7], while a typical mass flow rate is equal to 22 kg/s [8]. On the other hand, the hydrothermal carbonization process requires heat at a temperature of about 290ºC [9]. Thus, this sector has significant waste heat and the potential to upgrade medium-grade heat for process heating applications.

This study aims to develop a TCHT system to upgrade industrial waste heat to a higher temperature level and use it for process heating applications (here, the hydrothermal carbonization process). Our case study is the iron and steel industry due to its potential for waste heat and demand for process heating. This TCHT system upgrades heat from 230°C to 290°C. The proposed TCHT system operates with $SrBr_2.H_2O$ salt as a thermochemical material. The temperature range for $SrBr_2.H_2O$ is between 150°C and 300°C, which is suitable for our case study. Thermodynamic analysis is investigated for the proposed TCHT system, including energy and exergy analysis. According to energy and exergy analysis, the coefficient of performance of the system (COPh) based on thermal power and exergy efficiency are calculated, and the impact of design system parameters (e.g., condenser temperature) is investigated on COPh and exergy efficiency.

2. System Description

Figure 1 illustrates the schematic diagram of our proposed TCHT system for heat upgrading in the iron and steel industry. The major components of the TCHT system are an evaporator, a hydration reactor, a dehydration reactor, a condenser, a water receiver, and a pump. The process initiates at the dehydration reactor, where the endothermic reaction should occur. The iron and steel industry supplies industrial waste heat at 230°C and fed into a waste heat recovery unit. This unit uses air as the heat transfer fluid (HTF) that should provide the required heat to the endothermic reaction. In the dehydration reactor, our material absorbs heat and should be dehydrated, which means that the water content of the material is separate from the solid part. Therefore, $SrBr_2.H_2O$ as thermochemical material is converted to a solid part ($SrBr_2$) and a gas part (H_2O). After that, the gas part goes to the condenser; the condenser unit condenses the water vapor, which may be reused within the system. After the vapor has been condensed, it is then sent to a receiver to collect and store before being used again. The water pump in the TCHT system is responsible for pressurizing the water from low pressure (i.e. condensation pressure) to high pressure (i.e. evaporation pressure). In the evaporator unit, the water converts into vapor at high pressure. The waste heat recovery unit supplies the amount of heat needed for the evaporation process. Then, this water vapor is fed into a hydration reactor, which interacts with the solid part ($SrBr_2$) at 290°C. The reaction during the hydration reactor is exothermic; as a result, the amount of heat relates to the ambient at a higher temperature level. Finally, this heat can be used in the process heating applications in the iron and steel industry.

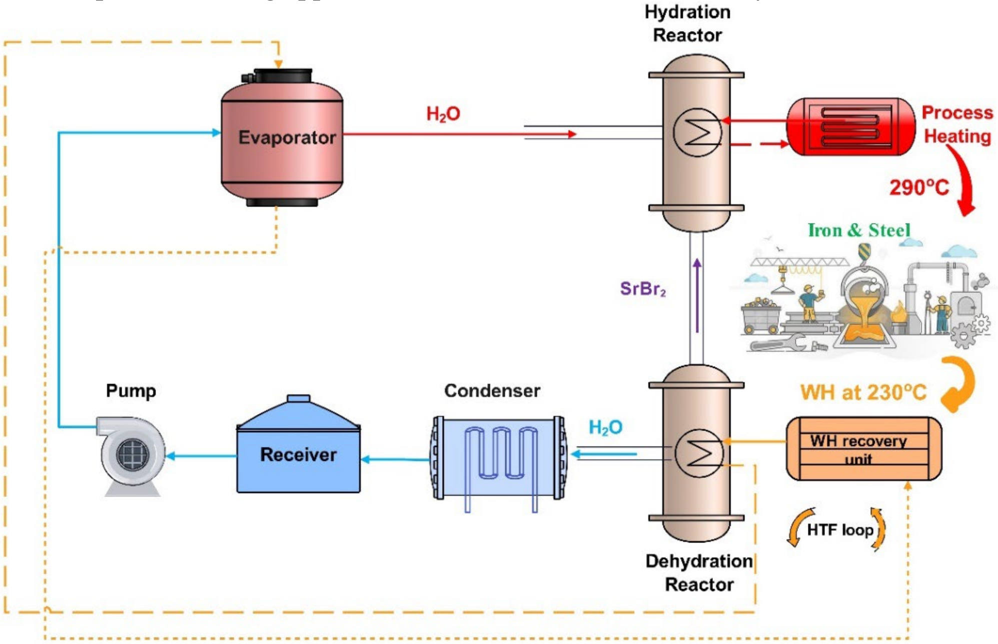

Fig. 1: Proposed TCHT system for heat upgrading in the Iron & Steel industry.

Table 1 provides detailed information on waste heat and process hearing in the iron and steel industry.

Table 1: Industrial waste heat and process heating in the Iron& Steel

Parameter	unit	Waste heat	Process heating
HTF-type	-	Air	Thermal oil
Tin	°C	230	265
Tout	°C	196.6	290
Mass flow rate	kg/s	65.9	46.3

Also, the design parameters of the proposed TCHT system are given in Table 2.

Table 2: Design parameters of the proposed TCHT system

Parameter	Value	unit	Parameter	Value	unit
System capacity	2.2	MW	Pinch temperature	10	K
Condenser temperature	35	°C	Heat capacity of air	1	kj/kg.K
Evaporator temperaturte	144.6	°C	Heat capacity of thermal oil	1.98	kj/kg.K

Dehydration temperature	300	°C	Time period for each cycle	1	hour
Dehydration temperature	186.6	°C	Isentropic efficiency of the pump	75	%

3. Thermodynamic Analysis

The reversible solid/gas reaction for the $SrBr_2.H_2O$ can be written as [10]:

$$SrBr_2.H_2O(s) \leftrightharpoons SrBr_2(s) + H_2O(g) + \Delta H_r \tag{1}$$

Also, the relation between the vapor pressure and reaction temperature for this material is defined by the van't Hoff equation as follows:

$$\log\left(\frac{P}{P^*}\right) = \frac{\Delta S_r}{R} - \frac{\Delta H_r}{RT} \tag{2}$$

In equation (1) and (2), R is the universal gas constant, P and T are equilibrium pressure and temperature, ΔH_r and ΔS_r refer to enthalpy and entropy of the reaction. Also, P^* is refrence pressure and equal to 10^3 kPa. The value of ΔH_r and ΔS_r for $SrBr_2.H_2O$ can be found in Ref. [10]. The mass flow rate of water dehydrated during the dehydration process can be calculated by:

$$\dot{Q}_{deh} = \dot{m}_w.\Delta H_r \tag{3}$$

where the $\dot{Q}_{deh}$ is the heat of dehydration and $\dot{m}_w$ is the mass flow rate of water. The following equation can calculate the amount of heat needed during the evaporator:

$$\dot{Q}_{eva} = \dot{m}_w.h_{fg}\big)_{T_{eva}} \tag{4}$$

In which, $h_{fg}\big)_{T_{eva}}$ is the enthalpy of evaporation at the specific evaporator temperature. The heat released to the industry as process heating during hydration processes ($\dot{Q}_{hyd}$) is defined as follows:

$$\dot{Q}_{hyd} = \dot{m}_w.\Delta H_r \tag{5}$$

The COPh of the proposed TCHT system is defined as the useful output heat to the useful supply heat to the system. Additionally, the exergy efficiency of the TCHT system can be defined as follows:

$$COPh = \frac{\dot{Q}_{hyd}}{\dot{Q}_{deh} + \dot{Q}_{eva}} \tag{6}$$

$$\eta_{ex} = \frac{\dot{Q}_{hyd}\left(1 - \frac{T_0}{T_{hyd}}\right)}{\dot{Q}_{deh}\left(1 - \frac{T_0}{T_{deh}}\right) + \dot{Q}_{eva}\left(1 - \frac{T_0}{T_{eva}}\right)} \tag{7}$$

3. Results and Discussion

Figure 2 illustrates the van't Hoff diagram for the proposed TCHT system. As can be seen, this diagram introduces the liquid/vapor equilibrium line for water (blue line) and the solid/gas equilibrium line for salt (green line). According to this figure, the theoretical temperature lift is equal to 113.4°C.

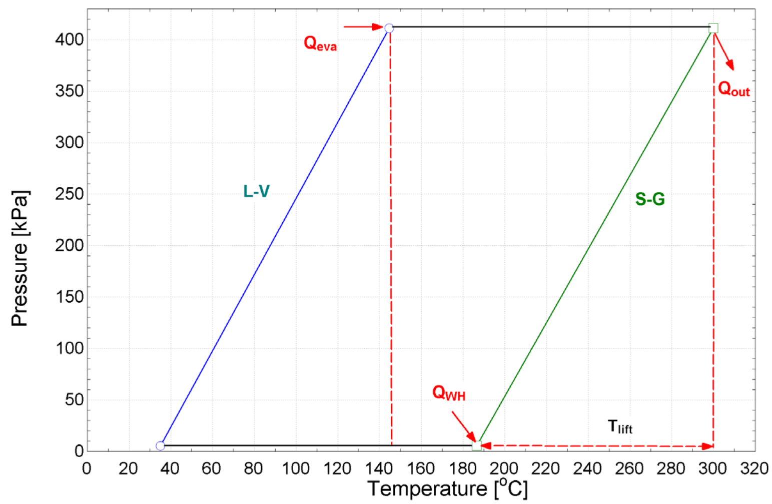

Fig. 2: van’t Hoff diagram for the proposed TCHT system.

The condenser temperature is equal to 35°C in the design conditions. Table 3 shows the results of the important parameters of the TCHT system under design conditions. It shows that the pump power in the proposed TCHT system is significantly low, resulting in minimal electricity demand. This is an advantage of our system: the proposed TCHT system can operate efficiently with reduced operational costs and lower dependency on electrical energy sources.

Table 3: Important parameters of the proposed TCHT system at design conditions

Parameter	Value	Unit	Parameter	Value	Unit
Mass of H_2O	1.98×10^3	kg	Heat transfer rate at condenser	1.332×10^3	kW
Mass of $SrBr_2$	2.72×10^4	kg	Pump power	0.2247	kW
Mass of $SrBr_2.H_2O$	2.92×10^4	kg	Heat transfer rate at evaporator	1.427×10^3	kW
Volume of reactor	21.96	m^3	COPh	0.6064	-
Exergy efficiency	89.3	%			

In the TCHT system, the condenser temperature is a key parameter. According to the van’t Hoff diagram, the dehydration reactor operates at the water pressure of the condenser. Thus, if the condenser temperature changed, the dehydration temperature changed too. Figure 3 illustrates the variation of dehydration temperature versus condenser temperature. In this study, the condenser temperature is assumed to be between 35°C to 70°C. The dehydration temperature varies between 186.6°C to 213.5°C.

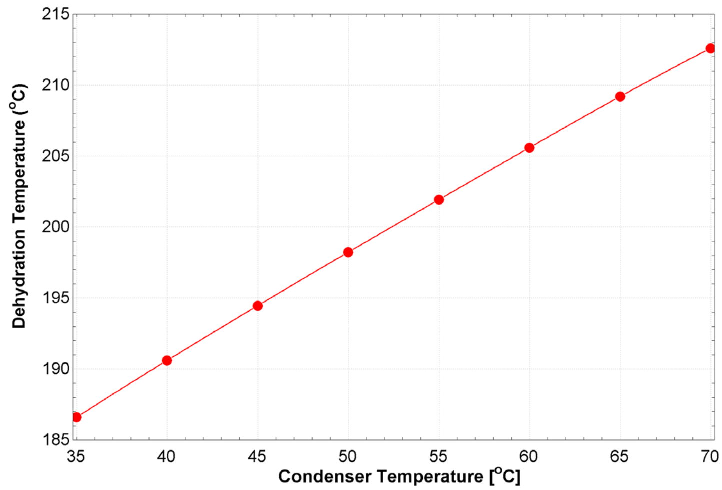

Fig. 3: Dehydration temperature versus condenser temperature

Figure 4 illustrates the impact of condenser temperature on the COPh and exergy efficiency of the system. As can be seen, the COPh of the TCHT system shows a slight increase as the condenser temperature rises. As a result, the condenser temperature does not significantly impact the COPh of the TCHT system. For instance, the COPh is 0.606 when the condenser temperature is 35°C and rises to approximately 0.622 at a condenser temperature of 70°C. On the other hand, the exergy efficiency decreases as the condenser temperature increases. For example, the exergy efficiency is 89.3% when the condenser temperature is 35°C and decreases to 85.5% at a condenser temperature of 70°C.

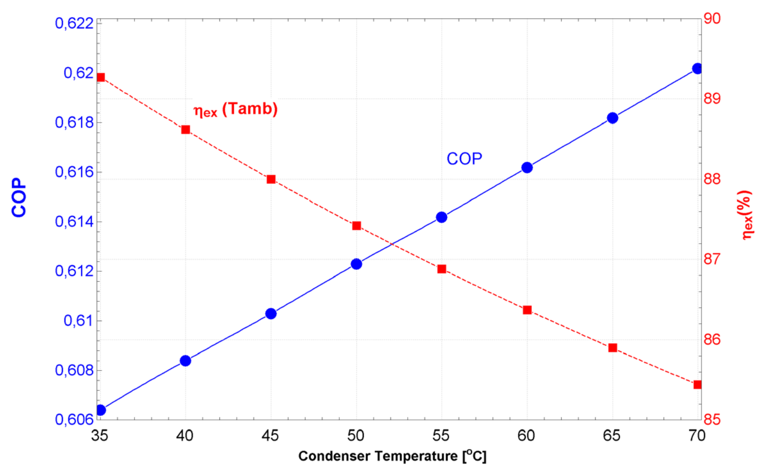

Fig. 4: COPh and exergy efficiency versus condenser temperature

Figure 5 shows the impact of the condenser temperature on the waste heat mass flow rate. As the dehydration temperature increases when the condenser temperature increases (see Figure 3), the waste heat mass flow rate should increase because the capacity and inlet temperature in the dehydration reactor are constant; therefore, the outlet temperature of HTF should be increased. As shown in Figure 5, the mass flow rate of waste heat is dramatically increased from 65.9 kg/s at a condenser temperature of 35°C to 300 kg/s at a condenser temperature of 70°C.

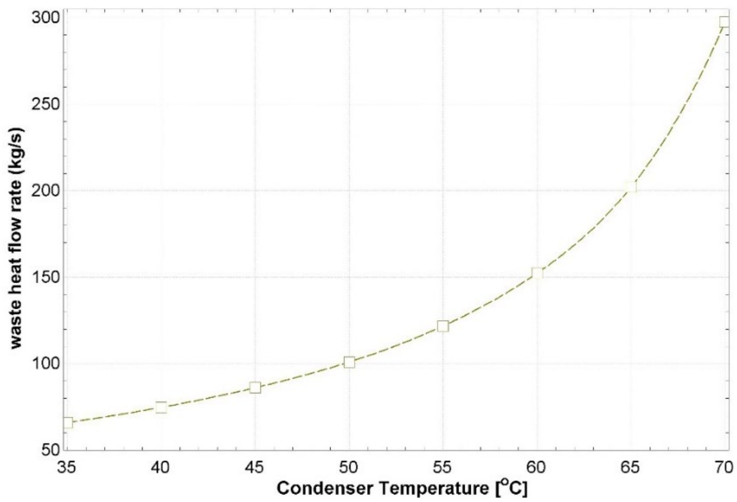

Fig. 5: Impact of the condenser temperature on waste heat mass flow rate

The impact of the condenser temperature on the size of the waste heat recovery unit is illustrated in Figure 6. According to Figure 5, the mass flow rate of waste heat increased when the condenser temperature increased. As a result, the size of the waste heat recovery unit (i.e. UA) should be increased. The value of UA for the condenser temperature of 35°C is 49 kW/K, while the UA is about 74 kW/K at the condenser temperature of 70°C. It can be found that the size of the waste heat recovery unit increased by approximately 53.5%.

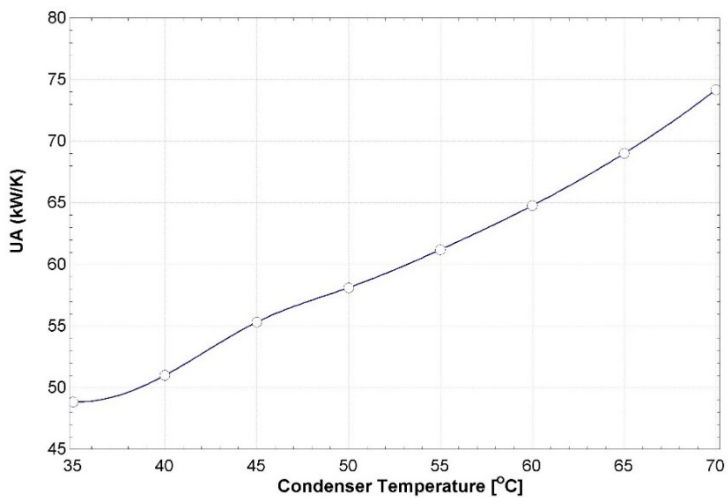

Fig. 6: Impact of the condenser temperature on the size of the waste heat recovery unit

4. Conclusion

The present study introduced the potentiality of TCHTs in upgrading industrial waste heat to a higher grade that is usable for process heating, especially for industries based on iron and steel. The proposed salt hydrate-based TCHT system in the present work can upgrade medium-grade waste heat with inlet temperatures as low as 230°C to as high as 290°C, meeting the requirements of applications like hydrothermal carbonization. The thermodynamic analysis illustrates that COPh lies between 0.6 and 0.62, with exergetic efficiency in the range of 85.5% to 89.3%, based on condenser temperature variations. Also, the TCHTs are capable of efficient heat recovery applications at minimal operational costs and electrical energy consumption, considering the very low consumption of pump electrical power. Besides, the analysis shows that design parameters, including the condenser temperature, play an important role in the system's performance regarding variations in dehydration temperature, the mass flow rate of waste heat, and the size of the waste heat recovery unit. The results show that the TCHT system can solve global challenges in the energy system and reduce carbon emissions in energy industries.

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