



## Improving high temperature heat capture for power generation in gasification plants

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### ABSTRACT

As part of the gasification process, hot syngas is cooled to low temperatures for gas cleaning by generating high pressure steam in a radiant heat exchanger. The steam, in turn, is used to generate electric power. However, the very large temperature difference that exists between the syngas and generated high pressure steam results in significant losses during the heat transfer process. These losses can be reduced, and hence the overall plant efficiency improved, by choosing materials and working fluids that reduce the temperature difference in the syngas heat exchanger. A set of alternatives to high pressure steam is liquid metals or molten salts. These liquids can be kept at a pressure equal to the syngas pressure, reducing the tensile hoop stress in the heat exchanger tubes. Since the strength of steel decreases with temperature, reducing the hoop stress allows tubes (and the liquids inside them) to reach higher temperatures. The liquid metals or molten salt can then be used in a secondary heat transfer loop to transfer heat to a steam generator. This paper describes a cost-effective radiant heat exchanger that can be used to transfer heat from high temperature syngas to these alternative heat transfer fluids, and also quantifies the increase in overall IGCC plant efficiency by doing so. A capital cost assessment shows a small payback time and improved revenue is achieved by using this technology, making this a realistic option for gasification processes.

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### 1. Introduction

Gasification is the process by which a carbonaceous fuel, such as coal, reacts with oxygen and steam to form synthesis gas (syngas), a mixture of hydrogen and carbon monoxide, which can be used to generate power, chemicals, or liquid fuels. The conversion of coal to electricity can occur in an integrated gasification combined cycle (IGCC) plant, which has higher a thermal efficiency and lower greenhouse emissions than a pulverized coal plant. As such, IGCC plants would benefit from innovations to improve heat capture for power generation.

The majority of commercial IGCC plants use entrained flow gasifiers that involve a variety of different syngas cooling strategies. Solid feedstock and oxidant are injected into the gasifier where they react at pressures of 2–7 MPa and temperatures of

~1300 °C. Following the gasifier, the syngas must be cooled to approximately 30 °C for mercury removal using a pre-sulfided activated carbon bed [1]. In the General Electric (GE) gasification process, high temperature syngas is cooled in a high temperature, radiant heat exchanger (also referred to as a radiant syngas cooler) and is used to boil high pressure (HP) water at 328 °C and 12.5 MPa. Boiling water inside the heat exchanger tubes leads to high heat transfer rates that keep the tubes outer wall cool. In the Shell Coal Gasification Process (SCGP) and ConocoPhillips E-Gas designs, a gas and chemical quench are used, respectively, to cool the gas to ~1000 °C before subsequent cooling to 316 °C in a syngas heat exchanger that generates high and medium pressure steam [2]. In all of these designs, heat transferred across a large temperature difference leads to significant losses.

To reduce the temperature difference between the syngas and the steam temperature must be increased. The challenge of absorbing heat by steam or any other heat transfer fluid at high temperature is that the maximum allowable hoop stress in the heat exchanger tubes decreases with increasing temperature. Furthermore, increasing the steam temperature is accompanied by an increase in steam pressure to maintain boiling heat transfer, which increases the hoop stress in the tube walls. To sustain higher pressures, thicker-walled tubes or higher strength, and oftentimes more expensive materials, are necessary.

*Abbreviations:* IGCC, integrated gasification combined cycle; CCS, carbon capture and storage; RHX, radiant heat exchanger; WGS, water gas shift; HP, high pressure; MP, medium pressure; LP, low pressure; LBE, lead-bismuth eutectic; GE, general electric; NETL, national energy technology laboratory; HRSG, heat recovery steam generator; HEN, heat exchanger network gas turbines; HHV, higher heating value; GT, gas turbine; ST, steam turbine; PL, parasitic load.

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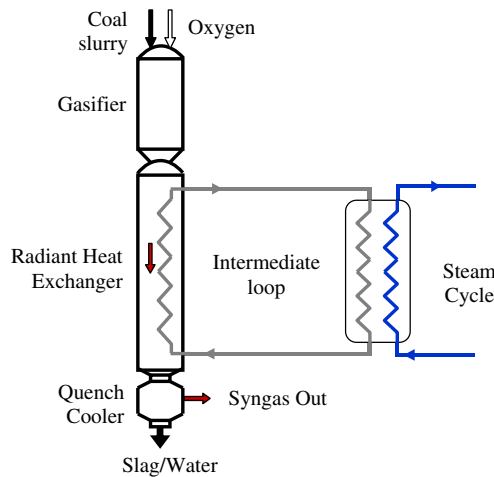


Fig. 1. An intermediate heat transfer fluid heats high pressure steam using heat absorbed from the radiant heat exchanger.

Based on this observation, the present work explores the use of alternative heat transfer fluids, tube materials and power cycles to reduce the temperature difference between the syngas and the heat transfer fluid within the radiant heat exchanger (RHX), thus improving overall plant efficiency. The main notion is to employ an intermediate heat transfer fluid to absorb the heat in the RHX at temperatures up to 660 °C, which is then forwarded to a secondary heat exchanger to generate steam at even higher temperatures and pressures than otherwise achievable in a conventional RHX. This concept is shown schematically in Fig. 1. The heat transfer fluid has excellent thermal properties to maintain a high heat transfer rate from the tube walls in the RHX. In the secondary heat exchanger, the heat transfer fluid is used to heat superheated steam because wall temperatures do not exceed the maximum temperatures of the materials commonly used in conventional steam superheaters. Not only is superheating of steam possible, but higher steam pressures including supercritical, >221 bar, are achievable because the temperatures of the tubes do not exceed the maximum temperature of high strength steels.

The GE gasification process has the largest temperature difference between the syngas and steam in the RHX as compared to other gasification processes (the syngas temperature enters the RHX at temperatures in excess of 1300 °C). In what follows, the cost of potential intermediary heat transfer fluids and compatible tube materials is discussed, as well as the resulting improvement in plant efficiency for the GE gasification process.

## 2. Material choices

### 2.1. Intermediate heat transfer fluid

In the nuclear industry, the exploration of heat removal with high temperature heat transfer is part of the Generation IV reactor program [3]. Reactor coolants that are being assessed are gases

such as carbon dioxide and helium, liquids such as molten metals and salts, and supercritical water. These same coolants can also be considered for use as a heat transfer fluid in a gasifier RHX. High temperature gases cannot be used in the RHX with conventional steel materials because their relatively low thermal conductivity and hence low heat transfer coefficients would result in high wall temperatures leading to material failure. Supercritical water would require thick-walled heat exchanger tubes to contain the associated high pressures and wall temperatures. Liquid metals and molten salts, compared to these aforementioned fluids, are advantageous because of their higher heat capacity per unit volume (leading to smaller heat exchangers), higher density (leading to a lower volume flow to reduce pumping power), and higher thermal conductivity (leading to lower wall temperatures).

A comparison of liquid metals and a representative molten salt is given in Table 1. As can be seen, molten salt has a higher viscosity ( $\mu$ ) compared to sodium, lead or lead-bismuth eutectic (LBE), which leads to low Reynolds number flows [4], and along with its lower thermal conductivity ( $k$ ), reduces its capability to draw heat from the tube walls. However, they are less corrosive and toxic, and do not react with secondary fluids [4]. Lead, LBE and sodium have comparable heat capacities per unit volume ( $\rho c_p$ ), but sodium has superior thermal properties due to its higher thermal conductivity. A major disadvantage of using sodium is that it can burn readily in air when heated (due to the presence of oxygen), and it reacts violently with water to form hydrogen gas, making its use a safety concern. Conversely, lead and LBE are chemically inert. Bismuth was eliminated because of its high cost, despite its good physical and thermodynamic properties.

In this work, the liquids that are assessed as heat transfer fluids are lead and LBE because of their excellent thermal properties, as well as molten salt because of its low toxicity. Lead is more attractive than LBE because of its lower cost and increased availability. However, the fusion temperatures ( $T_{fus}$ ) of lead and LBE of 327 °C and 124 °C respectively, making lead more susceptible to solidifying if heat sources are lost. To prevent solidifying during start up within the gasifier for all three liquid metals, the gasifier is first heated by burning natural gas before gasification occurs, which is already done in practice [7].

To select the molten salt for this application, a low melting temperature would be desirable to reduce the start-up and operating costs of heating pipes and vessels. Oxygen-containing salts (nitrates, sulfates, and carbonates) are not considered because they do not possess thermochemical stability at high temperatures [8]. These salts are also incompatible with carbon-containing materials because they release oxygen at high temperatures, which rapidly reacts with the available carbon. Other low temperature salts are excluded because they have a high vapor pressure ( $AlCl_3$ ,  $ZrCl_4$  and  $BeCl_2$  salts) or they are too corrosive (metal halides of Fe, Sn, Bi, Cd, Zn, and Tl) [8]. Heavy salts with their poor heat transfer characteristics and salts with more expensive bromine, iodine and rubidium components are also excluded. Fluoride salts have a viscosity that is almost five times larger than chloride salts [8,9], which reduces the Reynolds number of the flow and ultimately the heat transfer coefficient. Although they have slightly higher

Table 1  
Thermal properties of liquid metals and a molten salt. Data is given at 700 °C.

Name	$T_{fus}$ (°C)	$T_{boil}$ (°C)	$k$ (W/m K)	$c_p$ (J/kg K)	$\rho c_p$ (J/cm <sup>3</sup> K)	$\mu$ (Pa s)
Lead [5]	327	1620	19.9	145	1.48	$1.37 \times 10^{-3}$
LBE [5]	123.5	1670	16.7	139	1.37	$1.07 \times 10^{-3}$
Bismuth [5]	271.5	1560	16.3	132	1.26	$9.90 \times 10^{-4}$
Sodium [4]	97.8	892	59.1	1276	1.00	$1.81 \times 10^{-4}$
Molten Salt <sup>a</sup> [4]	396	2500	0.39	1004	1.72	$1.18 \times 10^{-3}$

<sup>a</sup> The salt chosen for this comparison is NaCl–KCl–MgCl<sub>2</sub> (30–20–50). Properties from Petroski et al. [6].

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