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A novel slag carbon arrestor process for energy recovery in steelmaking industry

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ABSTRACT

A novel slag carbon arrestor process (SCAP) was proposed to improve the heat recovery in energy-intensive steelmaking process, which typically has a low heat recovery. The proposed SCAP process introduces a tar reformer to utilise the slag - a by-product from steelmaking process - as the catalyst to convert coke oven gas and tar into hydrogen-enriched fuel gas. This is achieved by making use of the valuable carbon and/or energy contained in the coke oven gas, which otherwise being wasted, to assist in tar reforming and produce hydrogen-enriched gas. Such concept is expected to reduce the undesired tar formation in steelmaking process along with improved heat recovery efficiency and higher quality coke oven gas production. Both simulation and experimental studies on the slag carbon arrestor process were performed. The preliminary thermodynamic analysis carried out using Aspen Plus v8.4 indicates that with the tar reformer the energy content of coke oven gas was found increased from ~34.6 MJ/kg to ~37.7 MJ/kg (or by 9%). Also, with the utilisation of carbon deposition on the slag, a reduction of up to 12.8% coke usage in the steelmaking process can be achieved. This corresponds to an energy saving of 4% and a carbon emission reduction of 5.7% compared with the conventional steelmaking process. Preliminary experimental TGA-FTIR investigations revealed a reduction in the aromatic and aliphatic hydrocarbon groups and an increase in the production of CO_2 and CO, attributed to the tar cracking abilities of slag.

1. Introduction

Steel production is a major indicator for economy growth especially for developing countries. However, steel making is a highly energy intensive process accounting for nearly 5% of the world's total energy consumption and approximately 6.7% of total world CO_2 emissions. Also, the heat recovery in a steel making process is typically low at only ~17% [1]. The rising cost of energy and high demand for greenhouse gas emission reductions represent major challenges for the steel industry.

Currently, approximately 17% of the operating cost of the steelmaking industry is energy. This energy originates from multiple sources, such as coal, electricity, natural gas, recycled coke oven gas (COG) and blast furnace gas (BFG) [2]. Recycling of waste heat and recovery of energy rich by-products from these energy sources are identified as key measures to improve energy efficiency and reduce costs and emissions of the modern-day steelmaking process. It is estimated that the energy recycled from COG supplies ~20% of the total energy consumed in the present steelmaking process, with potential of increasing to 40% if fully utilised. BFG, on the other hand, has the potential to supply up to another 40% of the total plant energy consumption despite its low energy density (~1/3 of that of COG) [3].

Motivated by this path, our research team at the University of Newcastle, Australia developed a novel Slag Carbon Arrestor Process (SCAP) to improve the energy recovery of the steelmaking industry. The work is also part of a major research theme on low-emission energy technology options [4–10] being developed at the University of Newcastle, Australia. The SCAP process is to be introduced in the following texts.

Fig. 1 shows the conventional steel production process which primarily consists of two integrated unit operations: coke production and iron ore reduction. The coke making process involves carbonization of coal at high temperatures (800–1200 °C) in an oxygen deficient atmosphere in order to concentrate the carbon. During the coke making process, hot COG along with unwanted aromatic hydrocarbon compounds (i.e. tar) are generated, which contain valuable carbon and energy [1]. The produced COG is considered to be a good fuel source [11]. However, to ensure effective utilisation of COG, tar must be removed as it can create operational problems such as condensation and pipe blockages [11, 12]. To achieve this, the hot COG, at temperatures between 800 and 850 °C, emitted from coke ovens is spray cooled with an aqueous ammonia solution in order to remove most of the higher hydrocarbons in the tar, such as benzene (C_6H_6), toluene (C_7H_8), and naphthalene ($C_{10}H_8$). In addition, complex processing plants are required for the conversion of tar into valuable chemical by-products [13]. These processes, as mentioned by Yue et al. [14], cause significant heat losses and serious secondary pollution due to tar losses in the waste water. Therefore, instead of physically and chemically separating tar from COG, it would

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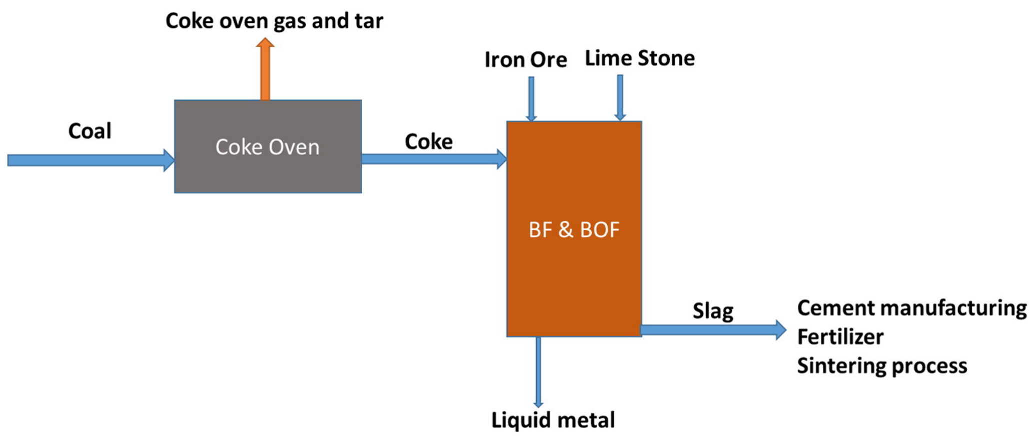

Fig. 1. Process flow diagram of a conventional steelmaking process (BF & BOF: blast furnace & basic oxygen furnace).

be highly beneficial if the tar could be decomposed into light fuel gases in-situ with the assistance of a catalyst. The heat and chemical energy embodied in the hot COG can also be used in this process.

After the coke making process, iron ore reduction and steel production occur in the blast furnace (BF) and basic oxygen furnace (BOF), respectively. Coke, sinter, and limestone are added in these two furnaces. The purpose of the blast furnace is to chemically reduce iron oxides into liquid metal and physically separate the liquid metal from slag. The operation of the blast furnace and basic oxygen plant usually results in the production of a high amount of slag, containing high amounts of CaO, FeO, SiO_2 and Al_2O_3 [15]. The majority of slag produced is currently used in the cement industry or as a fertilizer, while a fraction of the slag is recycled in the sintering process and in the blast furnace for supplying limestone and iron [16]. Heat recovery from slag is generally low and difficult due to its low thermal conductivity between 0.1 and 3 W/mK [17]. In general, this contributes to the low heat recovery of the steelmaking industry.

To overcome the aforementioned issues such as low heat recovery, high heat losses, and possible secondary pollution, several options have been suggested in the literature such as hot-slag heat recovery and more efficient process design [18]. Nonetheless those options are not fully developed for commercial implementation. As a step change solution, a novel Slag Carbon Arrestor Process (SCAP) was developed.

Fig. 2 shows the proposed SCAP process in which a tar reformer is introduced to the conventional steelmaking process. It is essentially the integration of a conventional steelmaking process and a tar reforming/hydrogenation process. In the tar reformer, tar decomposes under a catalytic reaction with steelmaking slag (see reaction R1) while COG is converted into a hydrogen-enriched gas [19],

$$\text{Tar} \rightarrow H_2 + CO + CO_2 + CH_4 + \text{other light hydrocarbon} + C. \qquad \text{(R1)}$$

Normally very high temperatures are required for tar decomposition; catalysts such as steelmaking slag can help to reduce such temperatures. Generally, calcium and iron are considered to be favourable catalyst materials for pyrolysis, reforming or decomposition of coal and/or tar as well as hydrogen-enriched gas production [20]. The innovativeness of the SCAP process is that the tar reforming process makes use of slag, which is rich in calcium and iron oxides, in the place of traditional calcium/iron oxide catalysts.

The slag entering into the tar reformer is best in the form of granulated slag (providing more surface area for catalytic reaction), which is a sand-like product produced using instant quenching of molten slag. Nevertheless, hot molten slag/rock type slag (produced by slowly cooling the molten slag) should not be excluded for future study. Also generated along with the tar reforming process is a possible soot formation/carbon deposition on the surface of slag, which can then be recycled back to the sinter machine and blast furnace. With such carbon recycling, the SCAP process is expected to not only reduce coke consumption in the steelmaking process, but also eliminate tar associated problems as well as the production of a hydrogen-enriched COG.

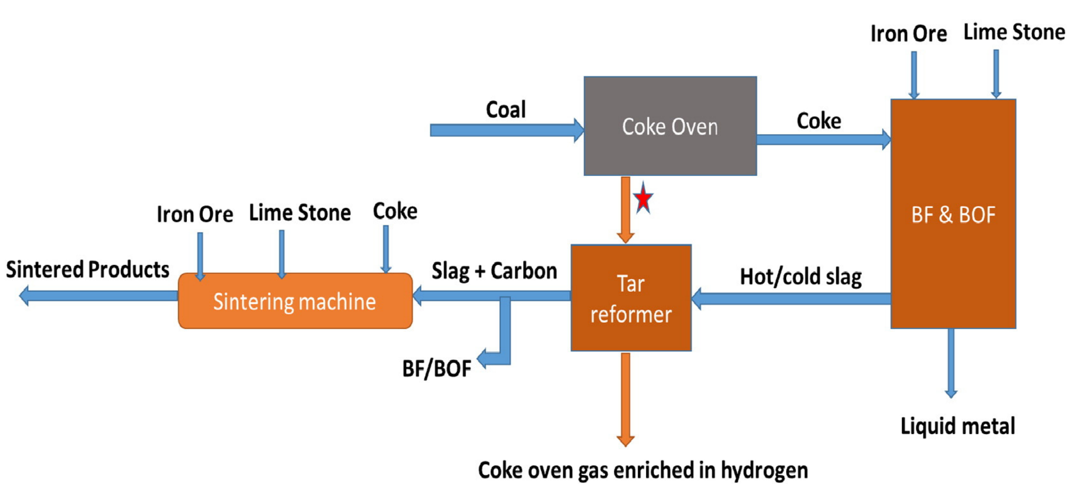

Fig. 2. Process flow diagram of the Slag Carbon Arrestor process for steelmaking (BF & BOF: blast furnace & basic oxygen furnace. *: potential energy recovery point).