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High Temperature Rheological Characteristics of Iron and Steel Making Slag and its Waste Heat Recovery-A Review

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Abstract

Rheological analyses of materials are essential/major branch of science and engineering which have received much attention. Their determinations having undergone high melting temperature materials requires specialist equipment to ascertain accurate rheological values during the processes. Although they have been an existed theoretical/semi-empirical models obtained from literatures, it is imperative to develop a specific mathematical models of rheological parameters from direct experimental data that best suits the metallurgical material. The environmental sustainability could be further enhanced through the recycle of these wastes into useful new products. This paper reviewed the high temperature rheological characteristics of slags and various methods used in recovery of waste heat during iron and steel making processing. Although chemical methods have been accepted by most researchers to be a better option for waste heat recovery, however, there is need for complex and multi-step technologies so as to obtain meaningful energy and material recoveries.

Keywords

Rheology, Iron and steel making slag, High temperature, Gas emission, Waste heat recovery

Introduction

Iron and steel making practice today is extremely complex in view of the optimization of the various unit processes with respect to the chemistry of the process, the technological aspect, process economy as well as environmental considerations. This industry is one of the most energy and CO_2-intensive industries [1-16] consuming around 9% of total anthropogenic energy [17,18] and accounts for about 20% of annual industrial energy utilization [11].

The metallurgical processes generate significant pollutant and greenhouse gas emissions, thereby causing serious environmental challenges [7,19-25]. Riley, et al. [26] estimated the CO_2 emissions/t steel for various countries. They included CO_2 emissions from electricity generation, using factors of 0.95 kg/kWh, 0.87 kg/kWh and 0.6 kg/kWh for coal, oil and natural gas-based power generation, respectively. Despite the differences on how iron, steel and electricity are produced in each of these countries, blast furnace iron making is the predominant source of steel mill CO_2. Iron and steel sector releases 7% of the total CO_2 emission [27-30] and 16% of the total industrial emission of CO_2 globally [31-33]. In Nigeria, this industry is endowed with all major raw materials needed for its production including over 3billion metric tons of iron ore deposits [34,35] 3 billion tons of coal [36], limestone in excess of 700 million tons and 187billion SCF of natural gas [37]. Although numerous advanced iron and steel making technologies have been implemented, the industry still faces a serious challenge of meeting the CO_2 targets when global emissions are cut to less than 50% of 2000 levels by 2050 [38,39]. Nevertheless, with the greenhouse gases (GHG) footprint, the material flows of this industry have been mapped by several studies [40-42], and researches on best way to utilize this CO_2 are currently on top gear. Iron and steel manufacturing industry has been capturing CO_2 from its flue gas with carbon-trapping technologies (e.g: Amine scrubbing, electrostatic precipitator) and recycling their waste products within the plant itself to limit excess handling and transportation of waste to disposal facilities [28].

The iron ore when exposed to high temperature using coal gasification happens to envelop different impurities and some of them like aluminium (Al), are the main structural constituents; while some, such as nickel, zinc and copper

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are part of the traced element fraction [43,44]. Sviridova, et al. [45] reported that a more intense extraction of iron will contribute to an increase in the temperature of the process, when conducting thermodynamics analysis. They also reported that the longer the slag melt is kept and the higher the temperature in the range 1300-1650 °C, the higher is the degree of metal recovery. Chen, et al. [46] investigated the thermodynamics properties for reduction of iron oxide ore particles in a high temperature drop tube furnace. They reported that at high temperatures (> 1660 K), the reaction of ore particle consists of the thermal decomposition and topo chemical reduction by the reducing gas. They also reported that the reduction degree of the ore does not increase obviously with the increase of temperature.

Iron and Steel Making Wastes and its Usefulness

During the iron, steel making and refining processes, several by-products such as slags (90% by mass), process gases, ducts, mill-scales and sludges are generated as metallurgical wastes [47-49]. Metallurgical slags constitute the largest by-product of the high temperature operations involved in the extraction and refining of metals whereas the dust and sludge removed from the gases consist primarily of iron and can mostly be used again in steelmaking. With increasing capacities, disposal of these large quantities of slag becomes a big environmental concern and a critical issue for iron and steelmakers [48]. This excessive slag could be classified as blast furnace slag and steelmaking slag. The blast furnace slag (BFS) depends on the speed of cooling which could be further categorized either as granulated slag (GBS), air-cooled slag (ABS), pelletized slag and expanded slag [50], whereas the steelmaking slag consists of basic oxygen furnace slag (BOFS), electric arc furnace slag (EAFS) and ladle furnace slag (LFS) [21,51-54]. This is summarized as shown in Figure 1 [54]. Granulated blast furnace slag is produced by quenching molten furnace slag with high-pressurized water. Blast furnace slags cooled in air constitute a crystallized material used as raw material instead of sand in the production of concrete. Blast furnace slag is obtained at high temperature and its viscosity is around 0.4-1.0 poise [55]. The largest is the output of blast furnace slag- per 1 ton of pig iron, which is 0.5-0.7 tons, while the smallest- when smelting steel in electric arc furnace is 0.1-0.4 tons.

During metal extraction, the rheological properties of the system change due to the transition from a one-phase liquid to a multi-phase suspension and the changing chemical composition of the slag. In iron making process, the metallurgical properties of blast furnace slags are determined largely by its viscosity hence high-temperature viscosity measurement is practically difficult, time-and-cost consuming. During the blast furnace operations, some solid phases such as oxide precipitates, coke or Ti (CN) can be present in the slag. In addition, the precipitation of solid particles was commonly observed in iron, steel, copper and other pyrometallurgy process. These solids can significantly increase the viscosity

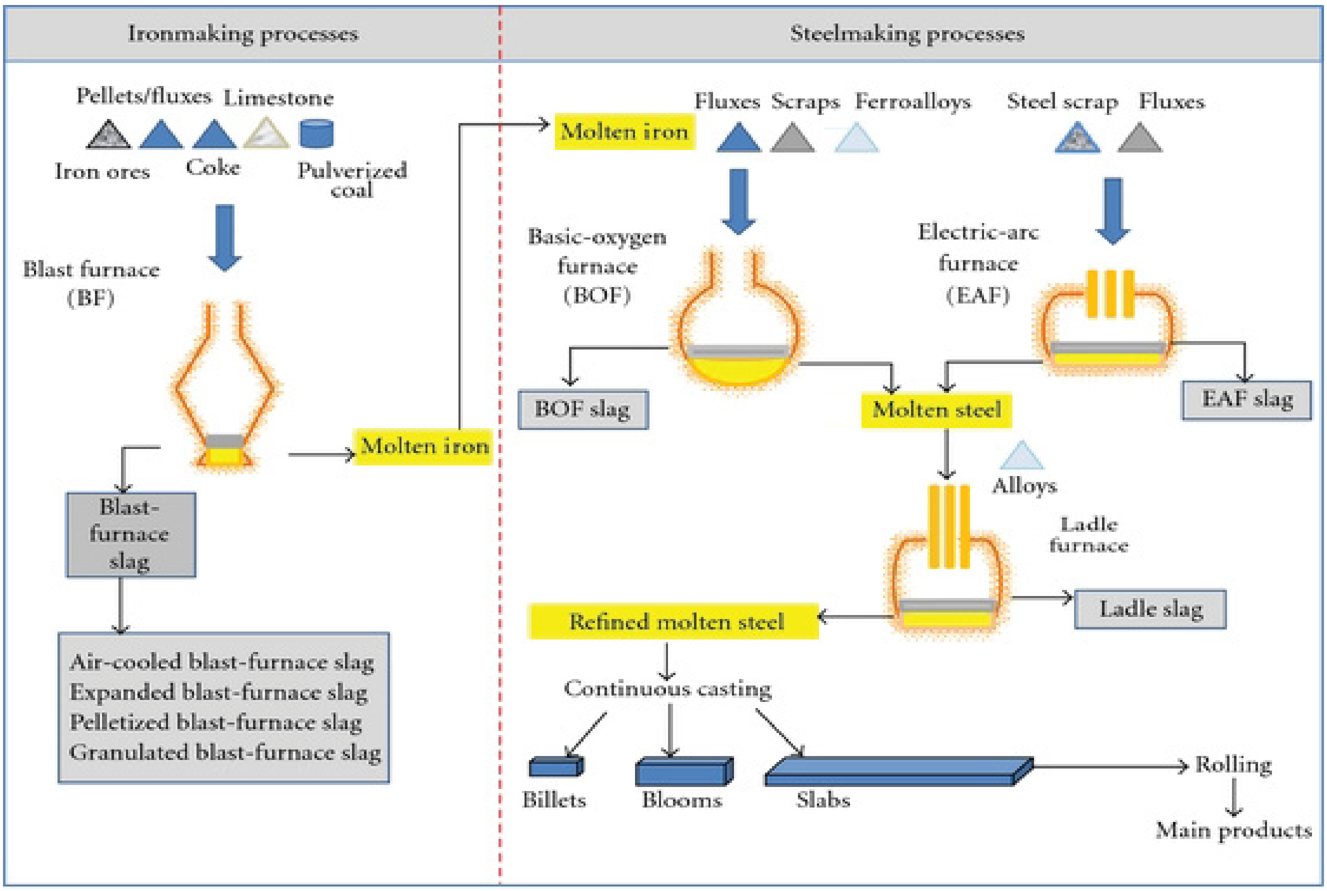

Figure 1: Flow diagram of iron and steel making processes [54].

Table 1: Chemical composition of iron and steel slag (wt. %) [63].

Furnace Type	CaO	SiO_2	Al_2O_3	MgO	MnO	TiO_2	FeO	P_2O_5	Cr_2O_3	Fe_2O_3
BFS	30-56	28-38	8-24	1-18	0.5-2	na	0.5-1	na	na	na
BOFS	30-55	8-20	1-6	5-15	2-8	0.4-2	10-35	≤ 2	≤ 0.73	na
EAFS	30-50	11-20	10-18	8-13	5-10	na	8-22	2-5	na	5-6
LFS	30-60	2-35	5-35	1-10	0-5	na	0.1-1.5	≤ 0.9	≤ 0.73	na

of the slag causing operating difficulty. Among various types of steel slags, basic oxygen furnace and electric arc furnace slags are the major by-products worldwide in terms of annual production quantities [56]. Slag has a specific heat capacity of 810 kJ/kg·K. The bulk density of steel slag lies between 3.3-3.6 g/cm^3, with water content of 3% ~ 8% [57]. In appearance, steel slag appears hard and wear-resistant due to its high Fe content. Slags are porous and have large surface area with suitable hydraulic conductivity [53,58]. According to previous studies, about 70% of the total production of blast furnace slag has been used as a replacement for Portland cement due to its numerous advantages, e.g., an increase in long-term strength and durability, decreased heat of hydration and the occurrence of the alkali-aggregate reaction. Only 1% of steel-making slag has been used as an admixture because steel-making slag has relatively low hydraulicity and has a problem with volumetric expansion [59]. The grind ability index of steel slag is 0.7, in contrast with the value of 0.96 and 1.0 for blast furnace slag and standard sand respectively [60,61]. The chemical component of iron and steel slag varies with the furnace type, its grades and pretreatment method. Table 1 [62] summarizes the chemical composition at different furnace slag.

Over 400 million tons of iron and steel slag worldwide are produced each year [47,51]. In 2019, world iron slag production was estimated to be between 320 million to 384 million tons, with steel slag production estimated to be between 190 million to 280 million tons. Quantities of iron ore type and ash of coke determines the variation of the different slags and its properties [63-68]. The cooling process of slag is the main reason for generation of different types of slag's required for various purposes. This slag has a worldwide average recovery rate from over 80% (steelmaking slag) to nearly 100% (iron making slag) [47] and could be well utilized in many industrial productions such as in building materials-cementitious material processing [30,52,54,56,57,65,69-86]; glass ceramic production [83,87-90]; fertilizer [57,65,91-94]; paint [47]; road construction [61,95-102]; water treatment [103,104]. Chemical composition of blast furnace slag has a significant factor in the potential performance of granulated material in cementitious uses. For chemical uses, such as a raw material for manufacture of glass or mineral wool insulation and for agricultural applications, the chemical composition is quite important. It is fortunate, therefore, that the range of slag compositions associated with good iron production is all useful construction materials, although varying in physical properties. The slag composition is also known to have adverse effects on the microstructure and its thermophysical properties, which causes inappropriate cooling of the slag to become weak thus restricting the reuse of slag in other industries [82,105,106].

Research advancement in the slag properties area have been examined over the years, which includes the cooling process [65,66,82,105,107-112] crushing and magnetic separation; basicity [113]; eutectic point [114] energy efficiency [82,115]; viscosity [116-123]; melting point [106,122,124-130].

Rheology described as a branch of science that have evolved from branch of physics, deals with deformation and flow of matter, has played a significant role in the analyses of iron and steel making slag characteristics [131,132]. The rheological behavior of any material is found to be between two limiting, ideal cases: The ideal solid body (Hookean body), which shows deformation proportional to the stress, and the ideal viscous material (Newtonian body), which shows rate of deformation proportional to the stress [133]. This has generated a relationships between stresses, strains, shear rates and time at which the slag has undergone to such a strain [116]. The viscosity of slag is distinctly dependent on the temperature and structure of the fluid. Many liquids, including most liquid synthetic and industrial slags, have shown a dependency of viscosity on the temperature in accordance with the standard Arrhenius-Guzman energy equation [134-137], given by the expression:

$$\log\eta = A + \frac{E}{T} \tag{1}$$

Where η is viscosity, ***T*** is temperature, ***A*** is fitting parameter and ***E*** represents the activation energy. Sridhar, et al. [138] reported that viscosities of molten metals and slags play vital roles in many high temperature phenomena that are important for advancing process control and product quality in molten-metal processing and casting. He stated that the need exists for reliable viscosity estimation methods based on the temperature and composition of the melt because measuring viscosities of high-temperature melts is expensive. Viscous flow in slag depends on the mobility of ionic species in the system, which in turn depends upon the nature of the chemical bond and the configuration of ionic species [139,140].

Rheological determination when heated at high temperature requires advanced specialist equipment which allows obtaining the high temperature readings inside during metallurgical processing of the material easier and also professional experienced personnel that can interpret the data obtained [116]. Experimental tests of physical properties as viscosity and surface tension of multi component systems at high temperatures (higher than 1500 °C) are difficult to carry out due to the complexity of the process and the amount of time involved. Thakur and Sarkar [141] reported that some magnetorheological (MR) devices reached high temperatures during operation and its strength gets affected as the temperature increases. The main task of rheology is to develop models to describe the behaviours of bodies that have been subjected to a force impact and several researchers have already carried out studies in this area using high temperature rheometer, also known as multipoint absolute viscometer to analyse both Newtonian and non-Newtonian fluids [116,142-145]. So far, measurement of rheological parameters, which includes the dynamics of the arc's influence on the properties of liquid steel and slag, dynamics of the influence of a reduction gas on liquid slag and pig iron in the blast furnace, the phenomena involving the move of semi-liquid and liquid products down the blast furnace in counter-flow with the reduction gas and then their flow down between the pieces of coke, are extremely difficult in its actual metallurgical processes [146]. It is also observed that the precision of temperature measurements is another major problem encountered during the metallurgical processing, of which the sample temperature is determined on the basis of temperature measurement conducted in the furnace [122]. Most numerical rheological models used in dynamic viscosity coefficient calculations of non-newtonian fluids largely depend on thermodynamic characteristics, which are gotten from the literature [117,147,148], however, there is urgent need to develop rheological models from experimental data suitable for iron and steel making processes.

Seok, et al. [149] reported that slag viscosities increase with decreasing temperature for almost all the slags that was investigated over a range of temperature range, and the slag viscosity exhibited different behavior in the temperature range lower and higher than 1773 K. They also reported that viscosity of the present slag systems decreased with increasing FeO content. Song, et al. [150] investigated the rheological behavior of slag experimentally using a high-temperature rheometer at temperature between 1200 °C and 1340 °C and correlated with the aid of computer software package Fact Sage. They result showed that the sensitivity of the slag viscosity to temperature decreases with increasing rotation speed. Jiang, et al. [151] carried out an experiment on the rheological properties of a blast furnace slag system using a high-temperature rheometer to reveal the non-Newtonian behavior of molten slag. They observed that molten slag exhibited the Newtonian fluid behavior when the temperature was higher than the critical viscosity temperature of the molten slag. In contrast, the molten slag exhibited the non-Newtonian pseudo plastic fluid characteristics and shear thinning behavior at temperature less than the critical viscosity temperature of the molten slag. Migas and Slezak [152] performed an analysis of high temperatures rheometry measurements. They observed at high temperatures, titanium oxide (TiO_2) may be reduced from the slag-liquid phase with the crucible carbon and titanium carbonitrides may precipitate and at lower temperatures, the perovskite phase may precipitate (apart from the existing high-melting solid particles). Wang, et al. [153] revealed the influence of basicity and MgO/Al_2O_3 ratio on the viscous behavior of CaO-SiO_2-Al_2O_3-MgO-$CaCl_2$ slags under conditions of C/S = 0.90-1.30 and MgO/Al_2O_3 = 0.40-0.67. They indicated that the MgO/Al_2O_3 ratio almost has no influence on the viscosity of the chlorine-containing slags at higher temperatures. Liu, et al. [139] investigated the effect of Al_2O_3 content on viscosity, and observed that the viscosity of blast furnace slag exhibits a constant declining trend as temperature increases and a turning point occurs in the viscosity-temperature curves under different Al_2O_3 contents. Jiao, et al. studied the effect of Al_2O_3 contents on the viscosity of SiO_2-CaO-MgO-Al_2O_3-FeO slag system at a fixed basicity of 1.3 as a function of temperature. They observed that increase in temperature smoothly decreases the viscosity in the fully liquid region and also, the slag viscosity increases rapidly as the temperature increases to a specific value. They also reported that influence of Al_2O_3 on the slag viscosity in different MgO content is too complex to distinguish easily. Shen, et al. [154] reported that when the temperature of the slag is lower than the liquid us temperature, the quantity and type of the phase has a significant influence on the slag system; and when the temperature is higher than the liquid us temperature of the slag, the viscosity of the slag system is mainly affected by the slag structure.

A total number of 2958 viscosity measurements from 582 compositions in the SiO_2-Al_2O_3-CaO-MgO system have been collected from 34 publications and these data have been critically reviewed for developing a viscosity model for iron and steelmaking slags [113,138,149,150,155-183]. Iida, et al. [178] measured the viscosity experimentally and validated the results of different models for different slag systems at various temperatures.

Iron and Steel Waste Heat Recovery

With the growing trend of increases in fuel prices over the past decades as well the rising concern regarding global warming, iron and steel industries are challenged with the task of reducing greenhouse gas emissions, saving energy and improving the energy efficiency of their sites [184]. In this regard, the use of waste heat recovery systems in iron and steel making processes has been key as one of the major areas of research to reduce fuel consumption, lower harmful emissions and improve production efficiency [47,185-193]. There are many types of waste heat energy in the process of iron and steel making and the amount of waste heat is relatively large [12,17,82,194]. This waste heat is mainly in blast furnace slag sensible heat, hot blast furnace cooling water, blast furnace gas sensible heat, hot air stove flue gas sensible heat and from the steelmaking processing units [195]. Approximately 0.3 tons of blast furnace slags (BFS) are produced for each ton of steel manufactured. This BFS came out at above 1773 K and each ton carried about 1.77 GJ of energy [196]. Consequently, about 235 million tons of BFS were produced with energy content of 4.16×10^8 GJ, which was converted into 14.20 million tons standard coal [5]. Therefore, it was of great significance to recover and utilize the high quality waste heat of molten BFS for iron and steel industry [4,197].

Waste heat is an invisible energy resource and can be categorized as follows according to the temperature: high temperature waste heat (above 650 °C), medium temperature waste heat (230-650 °C) and low temperature waste heat (below 230 °C), which are 3.36, 2.19 and 2.89 GJ/t steel respectively, equivalent to 287 kgce/t steel totally [8]. Current heat recovery solutions focus just on high and medium temperature waste heat because no opportunity to exploit low temperature waste heat exists within the iron and steel making plant. It is worth noting that low temperature waste heat currently represents a cost for the steel industry which must spend further energy to dissipate it. While low temperature waste heat has less thermal and economic value than high temperature heat, it is ubiquitous and available in large quantities. Hence, new technologies are developing that may provide significant opportunities for low temperature heat recovery. Waste heat can be rejected at any temperature; conventionally, the higher the temperature, the higher the quality of the waste heat and the easier optimization of the waste heat recovery process [189]. Key factors in determining the waste heat recovery feasibility includes: Heat quantity, heat temperature/quality, waste stream composition, minimum allowed temperature and operating schedules, availability. It is therefore important to discover the maximum amount of recoverable heat of the highest potential from a process and to ensure the achievement of the maximum efficiency from a waste heat recovery system. The recovery ratio of the high quality energy was less than 2% because of the basic constraints, i.e., low thermal conductivity-hindering heat extraction rate at sufficient rates, high crystallization tendency and discontinuous availability [12,17,96,198-201].

Waste energy recovery from iron and steel slag is difficult as heat removal results in a phase change from liquid to solid state. The formation of this solid slag on the surface of cooling slag inhibits heat transfer and solidification of the slag prevents circulation or movement of slag through heat exchangers and heat transfer devices. The use of slag product depends to a great extent on its mineragraphy, which is closely related to heat transfer and crystallization during the continuous cooling process [202]. In China, the molten steel slag temperature discharged in steelmaking process contains heat about 2000 MJ/t up to 1450 ~1650 °C, equivalent to 61 kg standard coals, belong to high-quality residual heat resources, great value of exploiting and utilizing. The thermal energy contained in the slag is equivalent to the energy in 12.3 million tons of coal equivalent [203]. Water quenching has been a traditional heat recovery technology which uses cold water to cool down slag but this technology consumes a huge amount of water and fails to recover the sensible heat energy of molten slag which is about 1.77 GJ/ton [82,124,204,205].

Generally, extensive traditional and advanced methods have been exploited and investigated to extract the waste heat of high-temperature slags, which can be classified into physical methods, chemical methods, thermal methods and direct electricity generation methods [95]. Heat energy of slag can also be recovered by both physical and chemical methods. Regarding the physical methods such as mechanical crushing, air blast and centrifugal granulating process, etc. are widely investigated. With respect to chemical methods, methane reforming reaction, biomass gasification and coal gasification process have been proposed [4,63,206-211]. As a traditional method, physical methods concentrate on the development of various granulation technologies through which the molten slags was granulated into small particles (GBFS) and the thermal heat in the slags exchanged with a heat transfer medium (air, steam, and phase-change materials (PCM)). Kasai, et al. [211], Shimada, et al. [212,213] and Mizuochi, et al. [214] suggested a dry granulation process without water quenching. When compared to water quenching, dry cooling method not only offered the basis for heat recovery from molten slag but also has the advantages of water conservation and no drying costs for slag utilization. Although physical methods were gradually reaching commercial testing and acceptance, they had obvious disadvantages which could be attributed to the fundamental constraints of heat recovery [17]. On the other hand, heat recovery through chemical methods has shown some specific advantages to meet these constraints. During the heat recovery using chemical methods, slags can act as not only heat carriers but also as good catalysts and reactants, which expand the field of utilization of slags [17,206,215]. For direct electricity generation methods combined with heat recovery from slags, the thermal energy could be exchanged and stored in the phase-change materials (PCM) and utilized for electricity generation using the Seebeck effect [17,216].

Shimizu, et al. [217] investigated heat recovery from molten BF slag using a fluidized bed vessel. In their laboratory-scale prototype, molten slag droplets were fed into a fluidized bed vessel consisting of crushed solid slag. The heat from the resulting phase change was recovered through boiler tubes. There was no direct contact between the BF slag and the boiler tube. Moon, et al. [218] reported that dry granulation processes based on air blast, rotating drums or spinning cup, recovers ~ 40 ~ 60% of the slag heat in the form of hot air at a temperature over 600 ^{O}C. The hot air could be used for steam generation or other on-site uses. Zhao, et al. [219] carried out feasibility of municipal solid waste (MSW) gasification using hot slag explored at 873-1173 K and it was found that the BFS acted as a catalyst & heat carrier which promoted the gasification reactivity of MSW. Chan, et al. [220] pointed out that recuperator installation is one of the most effective approaches of energy efficiency in reheating process in steel production; generally, it can achieve 10% heat recovery for reheat furnace.

Barati, et al. [82] evaluated these three technologies (physical, chemical and direct electricity generation methods) and found that, for both thermal & chemical energy recovery, a two-step heat recovery process would yield a high efficiency with minimal technical risk. Moreover, based on the inherent crystallization properties of slags [109,119], the heat recovery from slags should be divided into at least three stages. Luo, et al. [210] used biomass steam gasification recovering the waste heat of BF slag to produce syn gas. They made use of a moving-bed reactor and the results showed that BFS demonstrated good catalytic performance in improving tar cracking, enhancing char gasification and reforming of hydrocarbons; higher BFS temperature and smaller particles size can produce more light gases, less char and condensate. Using a similar experimental system, biomass pyrolys is using hot slags for bio-oil production was investigated at 773-1023 K [221]. It was found that an increase in slag particle size and biomass particle size decreased the production of bio-oil because of the change of heat transfer between slag particle and biomass particles. Analyzing the characterization of molten BFS waste heat and current energy situation of China. Duan, et al. [222,223] carried on rigorous research of utilizing coal gasification reaction to recover the high temperature and quality waste heat of BFS. Tobo, et al. [200] proposed a unique process of slag waste heat recovery. The sensible heat of the sheet-shaped slag was recovered by a counter-flow packed bed type heat exchanger and showed that the heat recovery ratio is over 30%. Motz, et al. [224] carried out research on dry solidification with heat recovery of ferrous slag. They reported that the waste heat of liquid slag during solidification in the range between more than 1600 and 1000 ^{O}C should be used to generate hot air, steam or electricity. Shachit, et al. [225] employed gas-solid indirect or direct contactor such as packed-bed, moving bed and fluidized bed contactor to recover heat from the dry slag granules. Liu, et al. [226] reported that in many dry granulation technologies, high temperature molten slag is atomized to slag particles and the thermal energy from high temperature slag particles are recovered by physical and chemical methods. They exploited gravity-bed waste heat boiler for thermal energy recovery from high-temperature slag particles and observed that an increase in Reynolds number (Re) showed no effect on the heat transfer coefficient or recovery efficiency. However, the heat transfer coefficient and recovery efficiency increased with a decrease in particle diameter and an increase in the velocity of descending particles. Yu, et al. [188] reviewed the granulation process for blast furnace slag. They reported that for every pig iron production accompanied by 0.3-0.6 tons of blast furnace slag produced with the temperature of 1350-1450 ^{O}C, 1600-1800 MJ sensible heat equivalent to 55-61 kg standard coal combustion after the heat generated. After thorough comparative analysis of water quenching and dry granulation processes, they concluded that centrifugal granulation affiliated with dry granulation was the optimum process, having smaller slag particle size (about 2 mm), more glassy phase and higher recovery rate. Liu, et al. [203] investigated waste heat recovery from high temperature blast furnace slag particles. A heat transfer models for packed bed, moving bed and fluidized bed to recover thermal energy from high temperature slag particles were established. Their results showed that the packed bed, moving bed and fluidized bed were not suitable for recycling thermal energy from slag particles with small diameter, high temperature and flowrate. Based on this problem encountered, they exploited a technique of thermal energy recovery from high temperature slag particles using gravity bed waste heat boiler to produce steam. Its heat recovery rate reached as much as 91%. Deng, et al. [227] studied air-cooling waste heat recovery from molten slag of slag-tap boilers. They reported that thermal efficiency of the boiler increased resulting in a decrease of fuel consumption rate. Renuka, et al. [228] suggested a suitable method for heat recovery from blast furnace slag in a steel industry using a suitable phase change material. The system used allowed capture of waste heat energy and was employable for generating power without using nonrenewable sources like coal, gas, etc. Zhang, et al. [8] examined various waste energy recovery technology, such as coke dry quenching (CDQ), combined cycle power plant (CCPP), waste energy recovery from Linz-Donawitz process, etc, which have been used widely and contributed a lot to the energy savings. They introduced two typical processes under development- vertical tank cooling system for sinter sensible heat recovery and the Organic Rankine Cycle (ORC) system used in recovering the waste heat from blast furnace slag quenching water for power generation. Li, et al. [229] investigated the thermodynamics analysis of waste heat recovery system using different methods to recover the sensible heat of molten BF slag. The results showed that the heat efficiency of physical methods was 76.9%, and the energy efficiency of recovery as steam was 34.2%, the heat efficiency of combined methods was 92.2%, and the exergy efficiency is above 60%. This signifies that heat efficiency and energy efficiency of combined methods were higher than that of physical methods.

Zhan, et al. [230] developed a new process for generating hydrogen-enriched syn gas by the coal gasification using molten BFS as heat carrier. Their result showed that the main gas components in the molten pool were steam, H_2, CO and CO_2. Duan, et al. [4,222,223,231] carried out an extensive research of utilizing coal gasification reaction in order to recover the high temperature and quality waste heat of blast furnace slag. Duan, et al. [231] proposed the multi-stage slag waste heat recovery system. They evaluated the proposed system in comparison with convectional water quenching method-open circuit process and latest dry slag granulation method and found out that proposed system has a good application potential in the aspect of energy conservation and emission reduction for iron and steel industry. Duan, et al. [5] also proposed a novel method of heat recovery system from blast furnace slag with coal gasification reaction to generate syn gas. Their result suggested that the optimal conditions for slag waste heat recovery were achieved at 1623 K and steam to coal ratio of 2. Sun, et al. [232] investigated biomass gasification using the waste heat from high temperature (1450-1650 ^{O}C) slags in a mixture of CO_2 and H_2O. Yao, et al. [198] proposed tar steam reforming recovering waste heat of BF slag and observed it was feasible. Zhang, et al. [233] and Kasai, et al. [211] have proved that it was feasible using chemical methods to recover the waste heat of hot slag. Wu, et al. [234] carried out analysis on the energy recovery of furnace slag from steel industrial and thermo chemical conversion of lingo cellulosic biomass. They reported that combination of biomass pyrolys is with heat recovery from molten slag is a feasible and economically applicable technology. Barati and Jahanshahi [95] investigated granulation and heat recovery from metallurgical slags. They reported that metallurgical slags carries a thermal energy equivalent to 40 Mt/year of coal and the slag-processing technologies are slowly converging around dry granulation combined with heat recovery.

However, Sun, et al. [20] summarized the various energy-saving technologies, energy flow types and energy saving potentials for iron and steel industry.

Conclusion

Understanding and controlling the behavior of the slag phase is crucial in improving the operational and economical efficiencies. High temperature rheological investigations of iron and steelmaking slags have been seen as a necessity during its processing. Most researchers have carried out extensive studies on this subject matter and its usefulness is unquantifiable. There is a large potential to reduce, reuse and utilize the energy consumption in the iron and steel industry through heat recovery from hot slags. Many methods have been exploited to extract this waste heat from slag. The chemical methods offer better production from slag heat but still face fundamental constraints and require complex, multi-step technologies to yield meaningful energy and material recoveries.

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