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Waste Heat Recovery using Phase Change Material Coupled Steam Generator

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Abstract: ***In order to allow the Waste Heat Recovery from the molten slag produced as a by-product in steel industries, a new type of waste heat recovery system based on use of Phase Change Material is proposed. An improvisation of Waste Heat Recovery system, in addition to previously proposed ideas is presented. A Rotary Cup Atomizer is used for granulation of molten slag and to bring down the temperature of the molten slag to a working range. The heat of slag is recovered using fluidized bed heat exchanger and further used to generate power by using Phase Change Material Coupled steam generator. A system combining Phase Change Material and Heat Transfer Fluid is used to smooth-off gas temperature profiles entering the steam generator. The Waste Heat Recovery system using Phase Change Material exhibits a great potential in the field of power generation from the untapped energy available in molten slag.***

Keywords: RCA, PCM, HTF, HESU

1. Introduction

Metal manufacturing industry has achieved tremendous improvements in its energy efficiency in the past several decades. Metallurgical slags constitute the largest by-product of the high temperature operations involved in the extraction and refining of metals. Slags are comparable to molten lava and are generally rich in silica (SiO2), alumina (Al2O3), and lime (CaO). Slag is formed from the refining reactions, remaining gangue of the ore, erosion of the furnace refractory, and the added fluxes. The molten slag is tapped at temperatures up to 1650 °C, carrying a substantial amount of high quality thermal energy. This energy is usually not recovered, as the slag is tapped and cooled slowly in the slag dumps or is rapidly quenched by water to make glassy granules that are used as feedstock for cement manufacturing. Over the past four decades, several processes have been proposed to recover the waste energy of slag as heat, electricity, and fuel, while none has been commercialized yet. This report proposes a new method of waste heat energy recovery.

2. Energy Recovery Methods

Currently, three types of technologies are under development for utilizing the thermal energy of slags; recovery as hot air or steam, conversion to chemical energy as fuel, and thermoelectric power generation.

2.1 Thermoelectric Generator

In thermoelectric energy conversion, electricity is generated through the Seebeck effect in which a voltage difference is generated in a conductor or semiconductor, due to a temperature difference in the material. For example, when a rod of metal is heated at one end and cooled at the other, the electrons in the hot end become more energetic and start to move towards the cooler end. This results in a positively charged hot end and a negatively charged cold end, which builds up an electric potential difference in the material. The thermoelectric voltage developed per unit of temperature difference is called the Seebeck coefficient. A schematic basic thermocouple can be seen in Fig. 1.

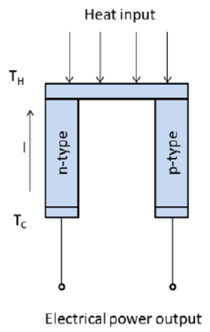


Figure 1: Schematic basic thermocouple.

The thermocouple is two semiconductors, one n-type and one p-type, which are connected in a circuit. When the junctions are set at different temperatures, TH (hot side) and TC (cold side), the Seebeck effect generates thermoelectric power.

A number of ideas are proposed for the recovery of heat from slag with using thermoelectric generator.

2.2 Recovery as Chemical energy

Generation of fuels based on the utilization of the slag thermal energy in endothermic reactions has been recently studied. As seen in Table 1, the following reactions have been proposed [1] to generate CO, H2, or their mixtures through gasification of coal, Reactions (1)e(2), reforming of hydrocarbons, Reactions (3)e(5), or decomposition of methanol, Reaction (6). In addition, the use of hot slag as a heat carrier and storage medium has been proposed [2,3]. Through this method, the thermal energy enables such endothermic reactions as phase change (such as melting of material) or other heat consuming reactions (for example decomposition of limestone, CaCO3→CaO + CO2, or melting), that could be later reversed to release heat. Fig. 2 depicts the scheme of this concept.

Table 1: Endothermic reactions for chemical recovery of waste heats [1]

Reaction		Enthalpy (kJ/mol)	Exergy (kJ/mol)
(1)	$C + CO_2 \rightarrow 2CO$	172	122
(2)	$C + H_2O \rightarrow CO + H_2$	131	91
(3)	$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	247	171
(4)	$CH_4 + H_2O \rightarrow CO + 3H_2$	206	142
(5)	$C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$	498	298
(6)	$CH_3OH \rightarrow CO + 2H_2$	90	25

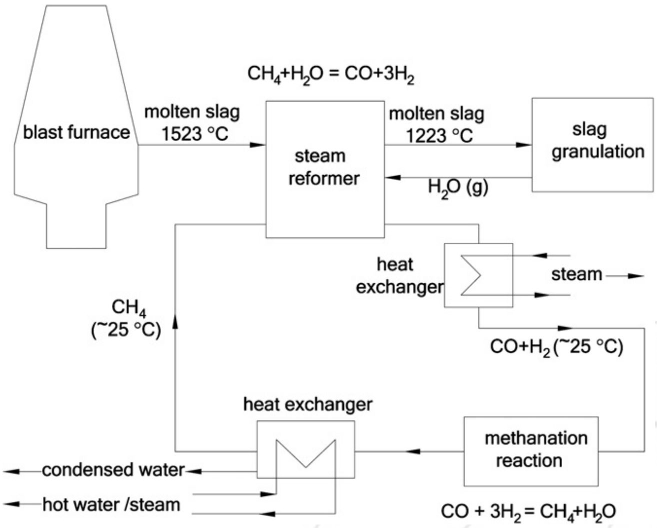
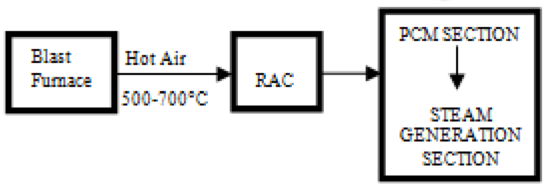


Figure 2: Process flow diagram for energy recovery through methane reforming [4].

3. Our Proposal

3.1 Concept

The temperature of the slag disposed from the Furnace is nearly 1500-1600°C. The practical working temperature of the Phase change materials (PCM) proposed for this system is below this temperature range (500-700°C). So to reach this lower temperature range, the use of Rotary Cup Atomizer (RCA) is proposed. The RCA lowers the temperature of the molten slag in the range of 900-1000°C by converting the molten slag to glassy granules. The heat is recovered from the granules with the use of fluidized bed heat exchanger. This heat is further used in the PCM coupled steam generator.



Novelty of idea-

There is no commercialized Waste Heat Recovery system available that uses PCM to extract the energy from molten slag. So far mainly Chemical Recovery systems are proposed that produces Hydrogen gas(fuel gas). ***In this idea the use of RCA is suggested to bring down the temperature of the molten slag at working range. A two stage fluidized bed is used to extract the heat from the granular slag, so that the value of heat extracted is more than that of proposed in previous ideas. After that, further harnessing the extracted energy in PCM coupled steam generator to produce power.***

3.2 Proposed Design and Working

The molten slag disposed from the furnace at a temperature range of 1500-1600°C is poured in the Rotary Cup Atomizer (RCA). The basic function of RCA is to change the molten slag into solid granular form by the centrifugal action of the cup.

The molten slag falls on the rotating cup which generally rotates at 500-1500 rpm which is sufficient to spread the slag into film and break it up. The wall of the RCA at which molten slag strikes is water-cooled. It results in the formation of granular slag having temperature in the range of 900-1000°C.

The granular slag is collected at the bottom of RCA. The heat from the granulated slag is extracted using **two stage fluidized bed heat exchanger**. The air is used as the fluid in the bed of granular slag. In the first stage the air extracts the heat from the molten slag that results in a drop in temperature of the slag and converting it into the granular slag. This is done by using two fans inclined at 45° from the vertical. The granular slag deposits at the bottom of RCA and constitutes in the second stage of fluidized bed. Using the air from another two fans placed vertically upward, the additional heat is extracted from the granular slag, resulting in the increased heat recovery. The schematic diagram of RCA with two stage fluidized bed is shown in Fig.3. After this the slag is disposed.

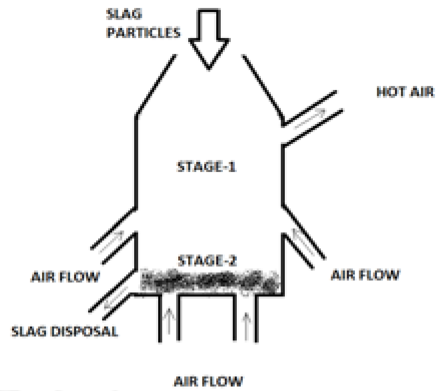


Figure 3: Schematic diagram of RCA with two stage fluidized bed

Now this hot air is directed to the PCM coupled steam generator. The PCM-coupled steam generator (see Figure 4) is composed by three sections: the PCM Section, the Steam Generation Section and the Auxiliary Section. The PCM Section is composed by a set of Heat Exchange and Storage Units (HESUs), which exchange heat with the hot air and the auxiliary heat transfer fluid (HTF) while charging or discharging the PCM. When the hot air enters the PCM Section, its temperature can be increased or decreased by the action of the HESUs. When hot air temperature is lower than the PCM melting point, in facts, the HESU releases latent heat from the PCM to the hot air increasing its temperature. On the contrary, when the hot air temperature is higher than the PCM melting point, the HESU absorbs heat from the hot air decreasing its temperature, while storing latent heat in the PCM. The combination of these two effects leads to smooth the hot air temperature, which tends to stabilize at the PCM phase transition temperature. After the PCM Section, the hot air enters the Steam Generation Section where it exchanges heat with the super-heater, the evaporator, and the economizer, thus generating superheated steam.

The Auxiliary Section connects the PCM Section and the

Steam Generation Section by providing the additional heat supply required to achieve constant steam parameters (mass flow rate and temperature) at the turbine inlet. In order to obtain a constant mass flow rate of steam, an auxiliary evaporator located downstream the evaporator of the Steam Generation Section is employed. To achieve a constant temperature of the superheated steam, instead, an auxiliary super-heater is installed downstream the super-heater of the Steam Generation Section. Both the auxiliary evaporator and the auxiliary super-heater are connected to the PCM Section by a closed loop circuit with a gaseous heat transfer fluid (HTF). Layout of our idea is shown in Fig. 4.

The Heat Exchange and Storage Unit (HESU) is composed by two coaxial pipes in which the gap between the inner pipe and the external one is filled with the PCM (Figure 5). The external pipe is in direct contact with the hot air, whereas in the inner pipe flows the heat transfer fluid used to feed the heat exchangers of the Auxiliary Section. Since all the HESUs within a given row undergo the same hot air thermal load, the same thermal power can be extracted from each of them by the HTF. Thus, HESUs in the same row should be connected in parallel by using a single inlet and outlet manifold, so that the same HTF control parameters can be applied to all of them.

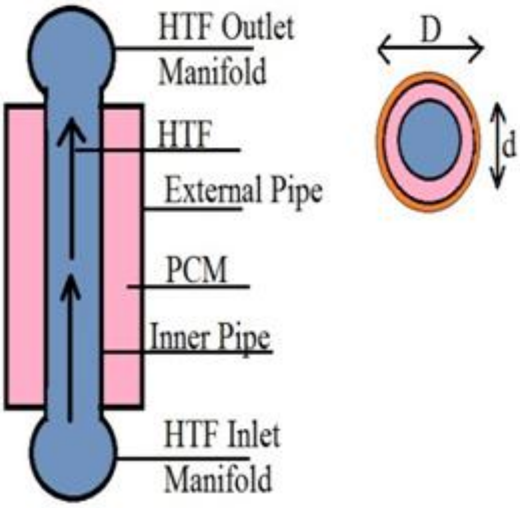


Figure 4: Schematic layout of our proposed idea.

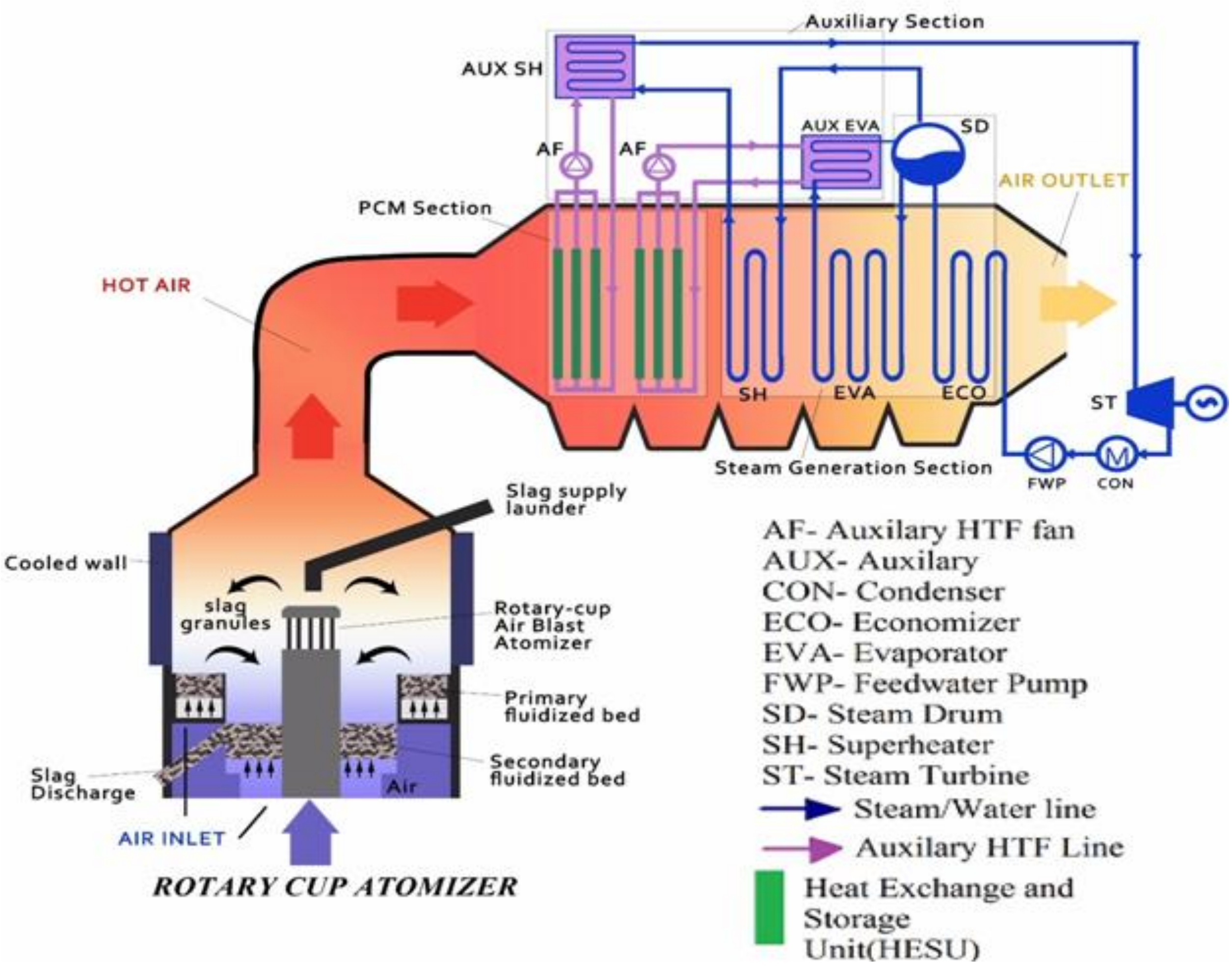


Figure 5: Schematic view of a single HESU unit.

As underlined in [5] and [6], metallic PCM has greater potential as high temperature PCM than molten salts, since metals generally have higher thermal conductivity and smaller volume expansion. In particular, Al–Si alloys represent the most promising high temperature PCMs for waste heat recovery from Furnace due to their suitable melting temperature, high latent heat of fusion and high thermal conductivity [7]. Al–Si alloys have highly corrosive nature to metals such as steel based-materials. A solution to this problem could be coating the steel walls in contact with the PCM with a thin film of Al2O3, which can be obtained by means of an aluminizing and oxidation treatment [8]. ***In this idea, alloy Al-12%Si (in mass %) has been chosen because it has one of the highest heat of fusion (560 kJ/kg) and thermal conductivity (160 W/m K) amongst Al-Si alloys; its temperature of fusion is about 576 °C.***

3.3 Calculation of Heat exchange in Fluidized Bed

The energy conservation in a slag droplet is given by Equation 1, where c_P is the molten slag specific heat, ε the emissivity, A_d cross sectional area of slag droplet, σ the Stephan-Boltzman constant and V_d is the volume of the droplet.

$$-hA_d(T_1 - T_0) - A_d\epsilon\sigma(T^4 - T_0^4) = V_d\rho_d c_p \frac{dT}{dt} \quad (1)$$

In the fluidized bed there will be no big temperature difference between the inside of fluidized bed and its walls, and so radiative heat transfer does not play a significant role in heat transfer. Thus, the Equation 1 is converted to Equation 2 given below.

$$-hA_d(T_1 - T_0) = V_d\rho_d c_p \frac{dT}{dt} \quad (2)$$

If this ordinary differential equation is solved, Equation 3 is obtained. In this equation, T_2 is the latest temperature of the slag particle during the heat transfer process, T_0 temperature of air and T_1 is the initial temperature of the molten slag (1450°C).

$$-\Delta t = \frac{V_d\rho_d C_p}{hA_d}\ln\left|\frac{T_2 - T_0}{T_1 - T_0}\right| \quad (3)$$

In order to obtain the latest temperature of the slag particles, convective heat transfer coefficient should be calculated. The convective heat transfer coefficient between a droplet and the air can be calculated by using the Equation 4 where Re is the Reynolds number and Pr the Prandtl number for gas, K_g thermal conductivity of gas and d is the diameter of the slag droplet [9]. The related parameters of the slag droplet and the air are given in Table 2, below.

$$h = \frac{K_g}{d}(2 + 0.6\sqrt{Re}\sqrt[3]{Pr}) \quad (4)$$

$$Re = \frac{\rho v d}{\mu} \quad (5)$$

Table 2: Constant, physical, and thermal properties of slag droplet and air [9]

Quantity	Value
Density of slag droplet(ρ_d)	3000 kgm−3
Dynamic viscosity of slag droplet (μ_d)	0.7 Pa.s
Density of air	1.184 kgm−3
Dynamic viscosity of air (μ_d)	1.849× 10^{-5} kg/ms
Specific heat of slag droplet (C_d)	1200 J/kgK
Initial temperature of slag droplet (T_1)	1450 ℃
Temperature of air (T_0)	25 ℃
Specific heat of air (C_g)	1007 J/kgK
Thermal conductivity of air (K_g)	2.6× 10^{-2} W/mK
Prandtl number of air at 25 ℃	0.7296

As it can be seen from Equation 4, velocity of slag droplets should be determined for calculating the Reynolds number to obtain convective heat transfer coefficient. In accordance with this purpose, it was benefited from force balance equation and Newton's second law. During the granulation process, tangential and radial velocity components occur and this velocity are calculated by using Equation 6 and 7 and the parameters of these equations are presented in Table 3 [9]. From these equations, tangential velocity and radial velocity can be calculated. Finally, resultant velocity of the slag droplet can be obtained by using Equation 8

$$V_t = \frac{\omega D}{2} \quad (6)$$

$$V_m = \sqrt[3]{\frac{\rho_d \omega^2 Q^2}{6\pi^2 D\mu_d}} \quad (7)$$

$$V_x = \sqrt{V_t^2 + V_m^2} \quad (8)$$

Table 3: Velocity parameters of the related equations

Quantity	Unit
Tangential velocity (V_t)	m/s
Radial velocity (V_m)	m/s
Angular velocity of granulator (ω)	r/min
Diameter of granulator (D)	m
Volumetric flow rate of slag	m^3/s

The vertical length between the RCA and the air fans is X meters and it is assumed that falling down of slag particles until the fan level takes t seconds. The acceleration of the slag particles can be calculated by Equation 9. The forces applied on a slag particle are illustrated in Figure 6.

$$X = V_0 t \pm \frac{1}{2}at^2 \quad (9)$$

After calculation of acceleration, the net force applied on slag particle can be calculated by using Equation 10. If the net force value is put into Equation 11, the drag force is calculated as F_D. In Equation 11, W represents the weight of the slag particles, C_D is the drag coefficient for slag particles and for spherical shapes. By using Equation 12, the resultant air velocity exerted by fan can be obtained as V_B for each fan.

$F_{net} = F_y = ma$

$$F_{net} = \rho_d V_d a \quad (10)$$

$$\Sigma F_y = W - F_D = ma \quad (11)$$

$$F_D = C_D A_s \rho \frac{v^2}{2} \quad (12)$$

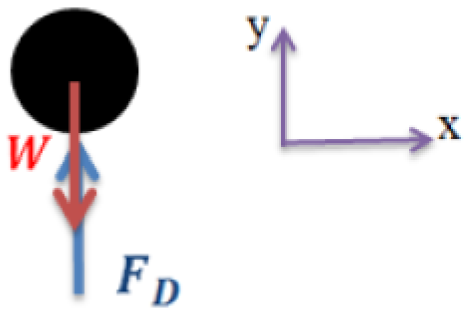


Figure 6: The forces applied on a slag particle

In first stage the fans are located at an angle of 45° with respect to fluidized bed, and velocity of fan air for each fan is calculated by Equation 13 as V_1=V_2 and the fans in second stage a relocated at an angle of 90° with respect to the fluidized bed and velocity of fan air for each fan(V_3) in second stage is same as VB. Furthermore, if the diameter of fan canal is selected as D_{fan}, the mass flow rate of air for each fan can be calculated by using Equation 15.

$$V_1 = V_2 = \frac{V_B}{\sqrt{2}} \quad (13)$$

$$V_3 = V_B \quad (14)$$

$$m_{fan} = \rho A V \quad (15)$$

After calculation of the air velocity, Reynold number can be easily obtained by Equation 5. Then, if the Reynolds number is used in Equation 4, the convective heat transfer coefficient is calculated as h. Thereafter, the convective heat transfer coefficient is substituted in Equation 3, discharge temperature of slag is calculated as T_2. Heat transfer during t seconds which occurs between the slag particles and the air is obtain by Equation 16

$$Q_1 = mC_d(T_{dis} - T_1) \quad (16)$$

$$Q_2 = mC_d(T_{dis2} - T_{dis}) \quad (17)$$

$$Q = Q_1 + Q_2 \quad (18)$$

Where, m is mass flow rate of molten slag, T_{dis} is the temperature of slag after stage 1 and T_{dis2} is temperature of slag after stage 2.

If the calculated values are substituted in Equation 16 and 17, heat transfer for first and second stages can be obtained as Q_1 and Q_2 respectively for the **m (kg/s)** molten slag production capacity. This heat transfer value **Q** is also equal to the energy change of the air. Thus, the outlet temperature of air (T_{ha}) can be calculated by using Equation 19, where C_g is specific heat of air.

$$Q = m_{fan} C_g (T_{ha} - T_0) \quad (19)$$

Thus using a two stage fluidized bed heat exchanger results in the increase in the amount of extracted heat and lowers the energy loss.

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