Application of Phase Change Materials in Heat Recovery from Blast Furnace Slag

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Abstract

The objective of this paper is to suggest a suitable method for heat recovery from blast furnace slag in a steel industry using a suitable Phase Change Material (PCM). The system will allow capture of heat energy, which is otherwise wasted, and it's employment for generating power without using non-renewable sources like coal, gas etc. The results show reduced material handling and generation of power equal to a small scale power plant. Rankine Cycle is employed to generate power.

Keywords — *PCM, Recovery, Slag, Rankine Cycle*

I. INTRODUCTION

Energy conservation has been the hot topic for nearly a decade. Various renewable sources have been proposed as an alternative energy source, like solar energy, tidal and wind energy. But these are mostly under development and require a completely new setup which increases their cost. Another method of energy conservation is to recover energy from places where it goes as a complete waste. This can be done by extracting energy from hot residual water from heat exchangers or as in Thermal Wheel or rotary heat exchange which consists of a circular honeycomb matrix of heat absorbing material, which is slowly rotated within the supply and exhaust air streams of an air handling system .[1]Similar methods can be employed in the steel industry.

The steel industry is energy intensive and consumes about 9% of anthropogenic energy and emitting large amounts of CO_2 into the atmosphere[2].In steel industry thermal energy can be extracted from the molten slag which goes off as a complete waste and can be reused for other purpose. According to the previous estimations [2], high temperature (1450–1550 °C) slags, carrying a substantial amount of high quality heat, represent the last potential source for energy reduction in the steel industry. About 1-2 GJ[3] of heat goes wasted in these slags. One way of extracting the heat from slag and effectively reusing is the storing the heat in form of latent heat of Phase Change Material and extracting it ,later for other use, as the material changes phase from either liquid to solid or from gaseous state to liquid state. Usually liquid- to -solid transformation is preferred since latent heat has higher value and also handling is easy. This concept is widely used in Concentrated Solar Power (CSP) generation systems.[4]

Yongqui Sun et al[2] presented in their technical paper the method to control heat recovery from blast furnace slag, by studying the time temperature transformation curves and estimating the most effective time period of heat recovery. The potential of heat recovery was calculated.

II. PHASE CHANGE MATERIALS(PCM)

A phase change material is a substance with high melting latent heat value: it stores or releases considerable amounts of energy, by melting or solidifying at certain temperature [5].

Early studies on PCMs were conducted by NASA for alimentation of satellites in orbit. A first classification of materials that exploit latent heat to store energy was given by A. Abhat in 1983 [6]

As shown in [7], Zalba et al. give a wide classification of best applications of PCMs:

—Thermal storage of solar energy.
—Passive storage in bioclimatic building/architecture.
—Cooling: use of off-peak rates and reduction of installed power, icebank.
—Heating and sanitary hot water: using off-peak rate and adapting unloading curves.
—Safety: temperature maintenance in rooms with computers or electrical appliances.
—Thermal protection of food: transport, hotel trade, ice-cream, etc. The food agro industry, wine,milk products (absorbing peaks in demand), greenhouses.
—Thermal protection of electronic devices (integrated in the appliance).
—Medical applications: transport of blood, operating tables, hot–cold therapies.
—Cooling of engines (electric and combustion).
—Thermal comfort in vehicles.
—Softening of exothermic temperature peaks in chemical reactions.
—Spacecraft thermal systems.

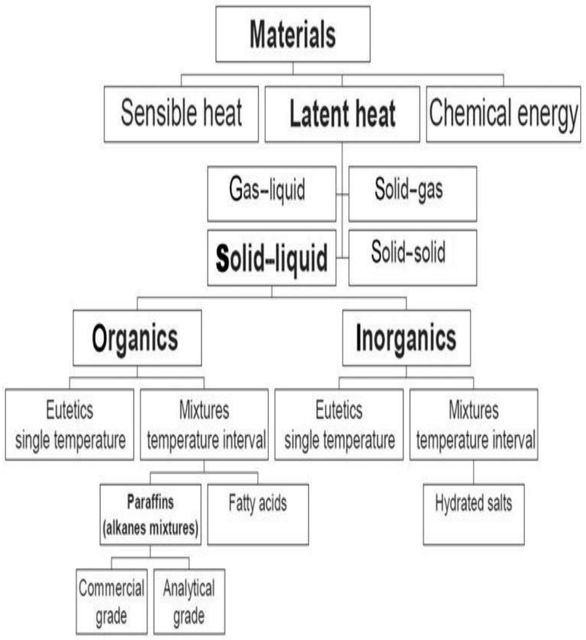

Fig 1: Classification of Energy storage materials[2]

A. Properties of PCM:

—High latent heat of fusion per unit mass, so that a lesser amount of material is required.
—High specific heat to provide additional sensible heat storage effect and also avoid subcooling.
—High thermal conductivity, so that the temperature gradient required for charging the storage material is small.
—High density, so that a smaller container volume holds the material.
—A melting point in the desired operating temperature range.
—The phase change material should be non-poisonous, non-flammable and non explosive.
—No chemical decomposition, so that the (LHTS) system life is assured.
—No corrosiveness to construction material.
—PCM should exhibit little or no supercooling during freezing

Latent heat thermal energy storage (LHTES) system using PCMs is a process near isothermal that can provide significantly larger storage capacity compared to sensible heat thermal energy storage (SHTES) at the same temperature range. Isothermal storage is an important characteristic because the variation of fluid temperatures of inlet and exit are constrained by the equipment and also the thermal power Rankine cycles [4].

As the storage capacity of LHTES system is governed largely by phase change latent heat which is seven times bigger than the sensible heat, it is possible to have smaller and lower cost thermal storage systems.

Latent Heat Thermal Energy Storage Systems have wide applications and if properly planned can even be used in the steel industry to prevent wastage of thermal energy untapped in slag from blast Furnace.

III.PROPOSED IDEA

The purpose of a blast furnace is to chemically reduce and physically convert iron oxides into liquid iron called “hot metal”. The final product of liquid iron and liquid slag are drained from furnace at regular intervals. The molten slag exiting from blast furnace is usually has a temperature range of 1000^{o}C-1200^{o}C[3].

All of this energy goes as a waste to the sink. This thermal energy can be tapped with the help of phase change materials. Using PCMs energy is recovered as well as the size of recovery and regeneration unit is reduced.

The idea of recovery is to utilize the heat extracted by the PCM for the purpose of running a power cycle. Rankine Cycle is a power cycle which works on steam. The main components of Rankine Cycle are:

1) Boiler
2) Turbine
3) Condenser
4) Pump

Now we know that steam is generated in the boiler. A conventional energy source like coal is the most common and economical source of heat generation for converting water to steam in boiler. This leads to wastage of energy. By using PCM the energy tapped from blast furnace slag can be used to heat water to steam instead of using coal or other energy source.

A. Recovery Unit

A unit needs to be designed where successive exchange of heat from molten slag to PCM and from liquefied PCM to water takes place. This unit consists of 2 chambers, one containing the solid PCM and other will be empty initially. As slag is led from blast furnace to PCM chamber, heat transfer starts and PCM turns into liquid. This liquid PCM is now transferred through pipes to the adjacent empty chamber. Now the empty chamber consists of water and steam pipes. As soon as molten PCM containing recovered heat is supplied in chamber, water is also supplied through pipes. This water will absorb heat from PCM and turn into steam. The steam is then fed to turbine for power generation.

The PCM on losing heat transforms back into solid state. Now the first chamber becomes empty and the empty chamber consists of solid PCM. Thus molten slag is now led to second chamber for heat transfer and steam is extracted from first chamber using the process as described above

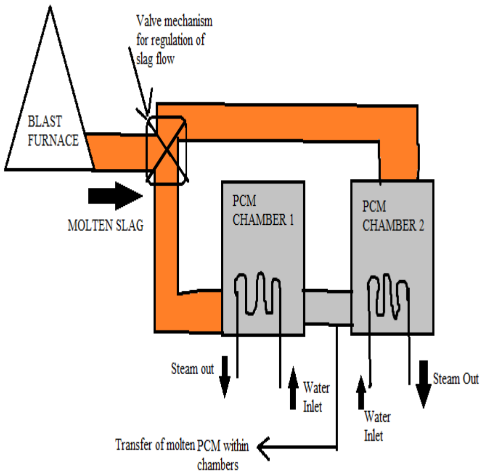

Fig 2: Flow diagram representation of heat recovery from Blast Furnace Slag

The above figure represents the proposed flow of slag and water, both of which interact thermally with the PCM. The structure is to be so designed that slag and water interact separately with the PCM Chamber. According to Fig 1 a valve mechanism needs to be established to regulate flow of slag to either Chamber 1 or Chamber2. As seen in fig 1, both chambers have pipes passing through them. A channel interlinking the chambers is used to transfer molten PCM from one chamber to another. Also water supply needs to be regulated such that it is in Chamber 2 for one cycle and for next cycle it is supplied in Chamber 2.This way heat recovery can be done continuously.

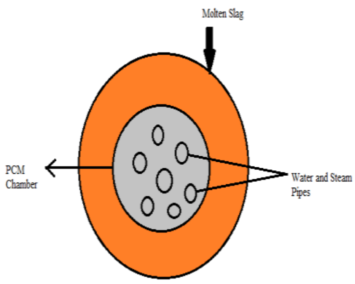

Fig 3: Schematic representation of top view of Single PCM Chamber

Further calculations for flow time of slag, time taken for PCM to melt, time taken for steam generation and time taken for liquid PCM transfer will be required to be done for assessment and designing of valve mechanism. This way Heat Recovered from molten slag can be used to generate power.

Other type of heat recovery units can also be designed, such as that designed for thermal energy storage system at high temperature for nuclear plants which acts as a single storage tank integrated with steam generator immersed in the heat storage coolant.[8]

B. Material Selection

PCM selected for heat recovery is NaCl. It is selected due to its high latent heat. It's melting point is high i.e. 800^{o}C [2] and is nearer to slag temperature. Thus it turns to liquid easily and due to high latent heat absorbs a large amount of heat for further use. It's density is 2160kg/m^3 [2] which facilitates for large mass in a small volume.[2**]**

C. Further Work

Further calculations which need to be worked upon for design and implementation of such a heat recovery unit are:

1. flow time of slag
2. time taken for PCM to melt
3. time taken for steam generation
4. time taken for liquid PCM transfer from Chamber 1 to Chamber 2.

These assessments will be further required to be done for designing and controlling of valve mechanism.

This way Heat Recovered from molten slag can be used to generate power.

IV. CALCULATIONS

The steam power is obtained by Rankine cycle.

Let 1 Kg of water is converted into 1 Kg of steam in the heat recovery unit. The PCM selected is **NaCl.**

Taking Power output from steam turbine=2MW
Melting Point of selected PCM (T_m)= 800^{o}C.............[4]
Latent Heat of PCM (NaCl)(L) = 492 KJ/Kg……….[4]
Specific Heat of NaCl(C_{NaCl})=0.864KJ/Kg K................[4]
Taking:
1) Ambient Temperature (i.e. initial temperature of PCM)(T_a) = 25^{o}C
2) Temperature of Blast Furnace Slag(T_s) = 1000^{o}C
Average Specific heat of Blast Furnace Slag = 0.945 KJ/Kg K.........[7]
Heat lost to PCM (KJ/Kg) = C_s*(T_s-T_m)
= (1000-800)*0.945
=189 KJ/Kg

Let 'm' mass of PCM is required for absorbing heat lost by 100Kg of Slag

→Heat lost by slag=Heat gained by PCM (Ideally)
→ $(T_s-T_m)C_s*m_s = m*L + m*C_{NaCl}*(T_m-T_a)$
→189*100 = m*492 + m*0.864*(800-25)
→m = 16.27Kg
Therefore it is seen that for every 100 Kg of slag 16.27 kg of PCM is required to recover heat.

This is the ideal case. Practically, heat transfer efficiency is not 100% .Thus more mass of PCM will be required.

Thus, based on above calculations the PCM is chosen to be NaCl

Slag Produced = 6T/Min

= 6000kg/min

= 100kg/s

Therefore, Heat available with 16.27 kg NaCl = 18900 KJ/s

=18.9MW

Taking Rankine cycle efficiency = 20%

→Power output = 3.78 MW

Therefore if slag production is 6T/min[3] , 3.78MW power Output can be obtained for which PCM required is 16.27 kg.

V. COST ANALYSIS

The cost of PCM material is considerably low and NaCl being the selected PCM it is very common and easily available.

Cost of NaCl per Kg = Rs 5-10/Kg

Taking average cost as Rs 7.5/Kg, we have

Amount of PCM required (as calculated above)= 16.27 Kg

→Total Cost = Rs 122

Which is a quite negligible input required in a steel plant.

The PCM is required to be input once and it will be recycled after each melting and solidification process. Thus, this investment has to be made only once.

Financial input will be required for setting up of a separate PCM storage unit and Further, huge amount of thermal energy is saved as well as the extra energy required to run a similar conventional steam power plant is also reduced.

Also we know that conventional power plants use coal for heat generation required for converting water to steam. The coal once burnt i.e converted into coke cannot be reused and each time fresh stock of coal is required to run the plant. This increases cost since each time investment needs to be done for material. Further, using PCM incorporated unit saves energy as well as non renewable resources like coal.

VI. CONCLUSIONS

The present study proposes a method to recover and utilize the waste thermal energy in an effective manner. An industrial prototype has been put forward which emphasizes on reduced thermal energy, material and money wastage. The results as obtained above show that by using 16.27Kg of PCM, 3.87 MW power output can be obtained by employing the Rankine cycle. Thus, small scale power plants can be run using this technique. The concept of Phase Change Materials has already been applied to areas like solar power plant and further work is required to be done for efficient development in this area.

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