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HEAT RECOVERY FROM MELTED BLAST FURNACE SLAG USING FLUIDIZED BED

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ABSTRACT

A novel fluidized bed system is proposed to recover heat from melted blast furnace slag. The melted slag is fed into a fluidized bed of crushed solid slag particles. The heat of slag solidification is transported to immersed heat transfer surface through fluidizing particles. The solid slag clumps, which consist of solidified slag and bed material, are removed from the bottom. A part of the slag clumps are crushed and recycled into the bed as bed material. In the present article, conceptual design of arrangement of heat transfer surface was carried out. Fundamental study of heat recovery from melted wax (simulated melted slag) was conducted using a fluidized bed cold model. Heat balance of the fluidized bed cold model was established.

INTRODUCTION

Blast furnace slag is a byproduct of iron making. For 1000 kg of iron, approximately 290 kg of slag is formed. When the melted slag leaves blast furnace, its temperature is about 1800 K. In Japan, approximately 24 million tons of blast furnace slag is formed annually (1). The heat of melted slag produced annually in Japan is estimated to be equivalent to 1.8 million tons of coal, which is about 1 % of total coal consumption (183 million tons (2)) in Japan. However, heat recovery from melted slag is not an easy task. With heat removal, the slag changes its phase, from liquid to solid, thus the direct heat recovery from the melted slag is not possible. At this moment, heat recovery from slag has not yet been conducted commercially.

Processes to recover heat from slag have been proposed. Heat recovery methods from solidified slag after cooling melted slag by air or water spray were proposed (3, 4) but these methods cannot make the most of high temperature energy of melted slag. Indirect heat recovery from high-temperature air generated by contacting air with melted slag (5) and from high-temperature steam generated by contacting water with melted slag (6) have been proposed, but these methods requires large heat transfer surface area due to low heat transfer coefficient in gas stream. An efficient heat recovery process that can recover high-temperature steam for power generation has not yet been proposed.

The authors propose a novel heat recovery system using a fluidized bed. The present article reports the conceptual design of arrangement of heat transfer surface. Fundamental study of heat recovery from melted material was conducted using a fluidized bed cold model by use of melted wax as simulated melted slag. Heat balance of the fluidized bed cold model was established.

PROCESS CONCEPTUAL DESIGN

Fig.1 illustrates the concept of fluidized bed process to recover heat from melted blast furnace slag. The melted slag is fed into a fluidized bed consists of crushed solid slag particles. With cooling, the slag release sensible heat and heat of solidification. The heat from the slag is transported to immersed heat transfer surface through fluidized bed. Thus direct contact between heat transfer surface and slag can be avoided. The solid slag clumps, which consist of solidified slag and bed material, are removed from the bottom. A part of the slag clumps are crushed and recycled into the bed as bed material.

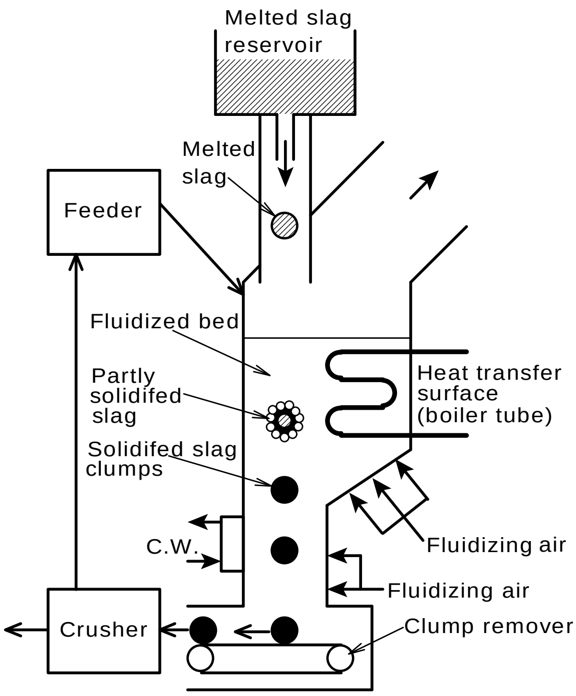

Fig.1 Fluidized bed process to recover heat from melted blast furnace slag

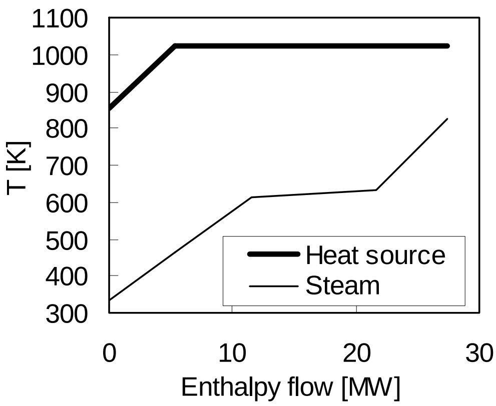

Fig.2 Enthalpy-temperature diagram of heat source and heat recovery as high-pressure (15 MPa) and high-temperature (823 K) steam

A conceptual design of heat recovery from melted slag at a feed rate of 100 t/hour is carried out. The feasibility to recover steam for power generation (temperature 823 K, pressure 15 MPa) is discussed. The temperature in the fluidized bed is assumed to be 1023 K, which is sufficiently lower than the melting point of slag. After solidification, the slag clump is assumed to be cooled down to 853 K at the bottom section between fluidized bed and clump remover. The heat released in the fluidized bed and the bottom cooling section is transferred to the steam. The enthalpy-temperature diagram of heat source and steam is shown in Fig.2. The temperature of the heat source is always higher than that of steam, thus heat recovery as high temperature and high pressure steam is possible.

Surface area for heat transfer in the bed is calculated. Temperature-resistant SUS304HTB tubes with outer diameter (D_o) of 48.6 mm and wall thickness of 7.1 mm was assumed. Feed water of 333 K is assumed to be heated up to 465 K in the bottom cooling section, then water is further heated to boiling point (623 K), evaporated, and finally superheated to 823 K. In a fluidized bed, overall heat transfer coefficient between bed and steam based on external surface area of a heat transfer tube is given as:

$$1/h = 1/h_o + (D_o - D_i)/2k_W + D_o/D_i h_i. \quad (1)$$

Heat transfer between outer surface of a horizontal tube and bubbling fluidized bed, h_o, is calculated according to the equation by Vreedenberg (7) as:

$$h_o D_o/k_f = 0.66(C_p\mu/k_f)^{0.3}[(U\rho_f D_o/\mu)(\rho_s/\rho_f)(1-\varepsilon_f)/\varepsilon_f]^{0.44} \quad (U\rho_f D_o/\mu<2000). \quad (2)$$

Heat transfer between inner surface of a tube and fluid (steam or water), h_i, is given as follows (8):

$$h_i D_i/k_f = 0.023(C_p\mu/k_f)^{0.4}(U\rho_f D_i/\mu)^{0.8} \quad (10000 < U\rho_f D_i/\mu < 120000) . \quad (3)$$

For the evaporation, heat transfer coefficient is usually larger than 1000 W/m^{2}K, and this is one order of magnitude larger than h_o. Thus the heat transfer resistance in the evaporation region is neglected. The estimated external surface area of boiler tubes is given in Table 1. By assuming horizontal tube pitch of 4D_o and vertical tube pitch of 2D_o, total volume of fluidized bed in which boiler tubes are immersed is calculated to be 51 m^3. If the bed height is to be 2 m, the horizontal cross sectional area is 25 m^2. A fluidized bed of this size is considered to be feasible.

Table 1 Estimation of heat transfer surface area of boiler tubes

	h_i [W/(m^{2}K)]	$2k_W/(D_o - D_i)$ [W/(m^{2}K)]	h_o [W/(m^{2}K)]	h [W/(m^{2}K)]	Q [MW]	ΔT_{typ} [K]	S [m^2]
Liquid	932	2619	282	182	6.1	480	70
Evaporation	>1000	2619	282	234	10.2	400	109
Superheat	180	2619	282	84	5.7	285	237

COLD MODEL EXPERIMENTS

Cold model experiments to feed melted material into a fluidized bed were carried out. The objectives of this cold model experiments were 1)to demonstrate smooth transfer of the heat of solidification to fluidized bed, and 2)to evaluate uptake of bed material into solidified material. For the former, theoretical model of change in fluidized bed temperature was compared with the experimental results. For the latter, separation of bed material from the solidified material followed by weight measurement was conducted.

Experimental apparatus is shown in Fig.3. A fluidized bed cold model of inner diameter 56 mm and height of 300 mm was employed. As bed material, quartz sand of average size of 0.15 mm was used. The amount of bed material was 300 g. Nitrogen was fed from the bottom at a superficial velocity of five times of minimum fluidizing velocity. Melted 1-hexadecanol (melting point 322 K, density 800 kg/m^3) was fed from the top of the fluidized bed as simulated slag. The temperature of the melted wax was fixed at 353 K. The flow rate of wax feed was controlled by a valve system installed at the bottom of the wax reservoir. During the experiments, temperature in the bed was continuously measured.

After experiments, all the bed material was removed. Clumps consist of solidified wax and quartz sand were separated from bed material by sieving with a sieve of 2.5 mm opening. The sand in the clumps was separated from the wax by melting the clump in hot water; the sand sank whereas melted wax floated. After separation, the mass of sand was measured.

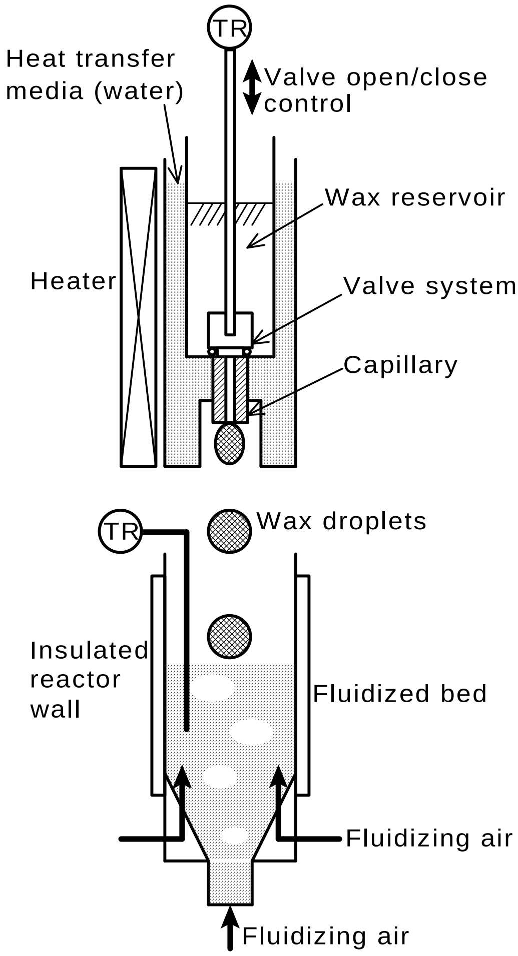

Fig.3 Experimental apparatus for cold model experiments to recover heat from melted material.

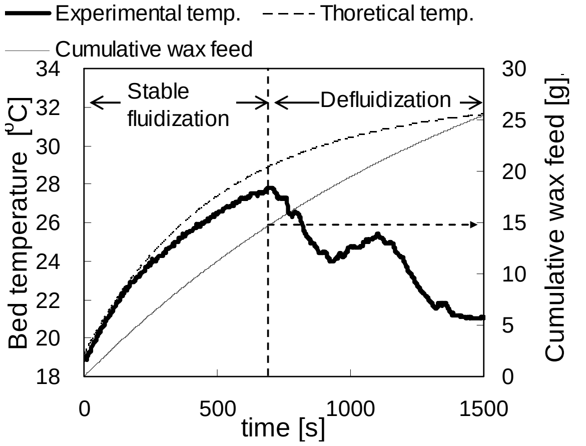

Fig.4 Change in fluidized bed temperature and cumulative wax feed with time.

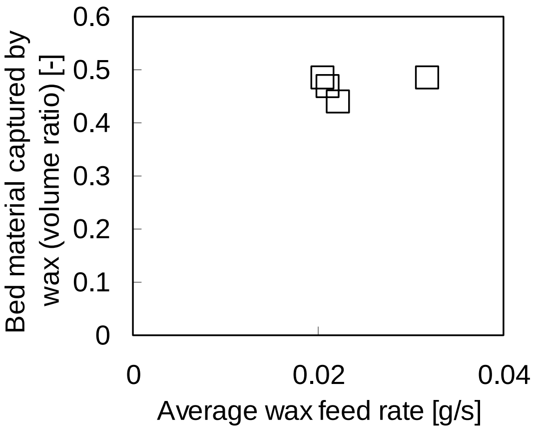

Fig.5 Effect of wax feed rate on uptake of bed material into solidified material.

RESULTS AND DISCUSSION

Fig.4 shows the change in fluidized bed temperature and cumulative wax feed with time. Smooth increase in bed temperature was observed for first 700 s after starting wax feed. This temperature increase is attributable to the heat input by the melted wax. However, at 700 s the temperature started to decrease. This decrease in temperature is attributable to defluidization due to accumulation of clumps of wax; the defluidization in the vicinity of the thermocouple inhibited the heat transportation from fed wax to the thermocouple, thus the thermocouple was cooled by fed gas. The defluidization took place when about 15 g of wax was fed to the bed, i.e. wax of about 17 % of bed material by volume caused the defluidization.

To avoid the accumulation of wax, drain of solid clumps from the bottom and feed of fresh bed material to compensate the loss of bed material are considered to be effective as shown in the concept (Fig.1). However, the present experimental apparatus was not equipped with drain/feed system. Continuous operation with solid drain/feed will be a subject of future work.

A model of temperature rise with wax feed was proposed. The heat input, q_{in}, is total sum of sensible heat and latent heat of wax as follows:

$$q_{in}=F_{wax}\{C_{pl}(353 - T_{mp})+H_{fus}+ C_{ps}(T_{mp} - T_{bed})\}. \quad (4)$$

Part of the heat is removed by gas stream and heat loss through wall as:

$$q_{out}=F_{gas}C_p(T_{bed} - T_{amb})+Ah_W(T_{bed} - T_{amb}). \quad (5)$$

Overall heat transfer coefficient between fluidized bed and surrounding air was experimentally determined in advance by filling the reactor with hot water and measuring change in water temperature. The overall heat transfer coefficient was 5.4 $W/(m^2K)$. The change in bed temperature is given by the accumulation of heat in the bed as follows:

$$(C_{pb}m_{BM}+C_{ps}m_{wax})(dT_{bed}/dt) = q_{in} - q_{out}. \quad (6)$$

It is assumed that the accumulated heat is uniformly dispersed in the bed due to good solid mixing. The model result of temperature rise is shown in Fig.4 compared with experimental result. As far as good fluidization is maintained, model result agreed well with the experimental result, i.e. heat of solidification of was dispersed throughout the bed.

Fig.5 shows the effect of wax feed rate on uptake of bed material into wax clumps. The uptake of sand was about half the wax by volume. Wax feed rate did not affect sand uptake. The bed material uptake is considered to be affected by interaction between bed material and melted material, i.e., wetting of solid by melted material, surface tension, and viscosity. Thus the uptake of the present quartz sand by present wax may be somewhat different from that for actual solid slag – melted slag system. Nevertheless, the present results of the effect of feed rate on bed material uptake suggest that feed rate has only minor influence on the bed material uptake.

CONCLUSION

A process to recover heat from melted blast furnace slag is proposed. A conceptual design of arrangement of heat transfer tubes is conducted. The size of fluidized bed is estimated to be feasible size. Cold model experiments to feed simulated slag (melted wax) into fluidized bed were carried out to evaluate heat transfer from slag to bed and to evaluate bed material uptake into the clumps. The experimental results show the feasibility of smooth heat transfer from solidifying slag to fluidized bed.

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NOTATION

A: surface area of reactor from fluidized bed bottom to bed height [m^2]
C_p: specific heat of fluid [J/(kg K)]

C_{pb}: specific heat of bed material [J/(kg K)]
C_{pl}: specific heat of liquid wax [J/(kg K)]
C_{ps}: specific heat of solid wax [J/(kg K)]
D_i: inner diameter of heat transfer tube [m]
D_o: outer diameter of heat transfer tube [m]
F_{gas}: gas feed rate [kg/s]
F_{wax}: wax feed rate [kg/s]
G: mass flow rate of fluid per unit cross sectional area [kg/(m^2 s)]
H_{fus}: heat of fusion of wax [J/(kg K)]
h: overall heat transfer coefficient between steam and fluidized bed [W/(m^{2}K)]
h_i: heat transfer coefficient between fluid and inner wall of tube [W/(m^{2}K)]
h_o: heat transfer coefficient between fluidized bed and outer wall of tube [W/(m^{2}K)]
h_W: overall heat transfer coefficient between reactor and surrounding air [W/(m^{2}K)]
k_f: thermal conductivity of fluid [W/(m K)]
k_W: thermal conductivity of material of boiler tube [W/(m K)]
m_{BM}: mass of bed material [kg]
m_{wax}: mass of wax in bed [kg]
Q: heat recovery [MW]
q_{in}: heat input to fluidized bed [W]
q_{out}: heat loss from fluidized bed [W]
S: external surface area of boiler tubes [m^2]
T: temperature [K]
T_{bed}: bed temperature [K]
T_{amb}: ambient temperature [K]
U: superficial gas velocity [m/s]

Greek symbols

ε_f: void fraction in fluidized bed [-]
μ: viscosity of fluid [kg/(m s)]
ρ_f: density of fluid [kg/m^3]
ρ_s: density of solid [kg/m^3]

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