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Mathematical Modeling for Green Cupola

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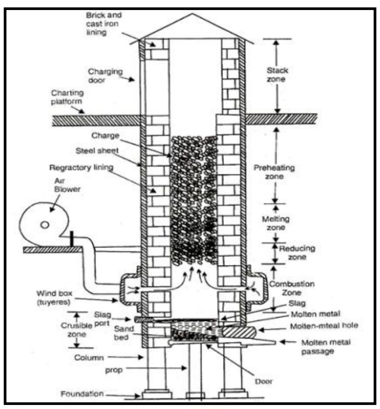
ABSTRACT

A cupola can be defined as a refractory lined cavity with necessary openings at the top for the escape of the off gasses and charging of the stock, at the bottom for entry of air blast, and drawing off the molten metal and slag. A bed of fuel is laid at the bottom of the cupola, which requires for ignition, following by alternate layers of metal, fuel and flux being charged and blast is then turned on. The cupola is the cheapest iron melting shaft furnace but emitting too much Solid Particulate Matters (SPM), SO_x , NO_x etc. This paper presents the modeling of a new kind of green cupola aiming to reduce the high emission level of SO_x by replacing coke partially or fully with biofuel as well as effective gainful utilization of biowaste.

Graphical Abstract



Greener perspective of using biowaste rice husk with coke in cupola, where followings could be achieved up to certain extent -

- Technical impact – Less SO_x emission
- Commercial – low cost

- Utilization of waste byproduct

Less GHG gas emission

Keywords: Cupola, Induction furnace, Cokeless cupola, Divided Blast Cupola (DBC), SO_x, SPM, Green House Gas (GHG).

INTRODUCTION

The cupola is a vertical cylindrical furnace built of steel plates and lined with firebrick or with monolithic refractory material [1-2] The lower portion is ringed by a wind box and air chamber, from which air blast enters the cupola through tuyeres to support combustion. A charging door, usually located some 20 ft. above the bottom of the furnace, permits loading the cupola with fuel (coke) and the materials making up the charges. In charging, a bed layer of fuel-coke is placed at the bottom of the cupola, with a layer of the other charge materials above it and layers of coke and charge alternating thereafter up the stock of the cupola to a predetermined height below the charging door. As combustion proceeds, the molten metal may be drawn off directly, or it may flow into fore hearth for subsequent transfer for duplexing. The first patent of modern cupola was taken in England in the year 1794 [3]. In next two hundred years, cupola undergone many changes in design and operation. To name a few, they are divided blast operation, oxygen enrichment of blast, oxygen injection, water cooled cupola etc.

MATERIALS AND METHODS

Two types of reaction happen in cupola, viz. oxidation and reduction [5-10]. Carbon, silicon, manganese is oxidized either by the free oxygen or the iron oxide of the slag. Carbon and carbon monoxide are the main reductants and they reduce silica, manganese oxide and aluminium oxide to their respective elemental form. Divided blast cupola has the advantage of higher melting temperature, lower coke charge consumption, better carbon pickup and least emission of carbon monoxide and solid particulate matter (SPM). But many of the changes were not accepted initially due to higher capital investment and increased operating cost. The ferrous foundries in Eastern India use high coke ash [11] (>30% ash) producing high solid waste, gases, thermal emission etc. The Cokeless cupola [12, 13] using fuel LDO or natural gas or propane emits low level sulphur dioxide. But due to high cost of refractory ball and graphite for carbon pickup, such cokeless has not been not popularized. Clean Development Mechanism (CDM) [14] is a mechanism, which along with energy efficient Divided Blast Cupola (DBC) technology to bring about energy productivity in Indian foundries. But till date no attempt was made to replace coke by bio fuel partly or fully to make cupola green. Cupola is the primary iron melting furnace of the foundry for many years [5]. Combustion of the coke occurs near the bottom. As the coke burns, hot off gasses rise along the entire length of the stack causing heating and melting of the charge metal. The molten metal descends through the porous traps of the coke bed and tapped out at the bottom of the furnace just below the combustion region. During the melting process, various metallic oxides and other non-metallic gangues accumulate and form slag, which floats on the molten metal and is removed before tapping the molten metal. The majority of the slag originates from the ash present in the coke. The basic fuel is coke, which provides heat as well as acts as the source of carbon for the product metal. Coke addition varies from 13 to 18% of metal charge.

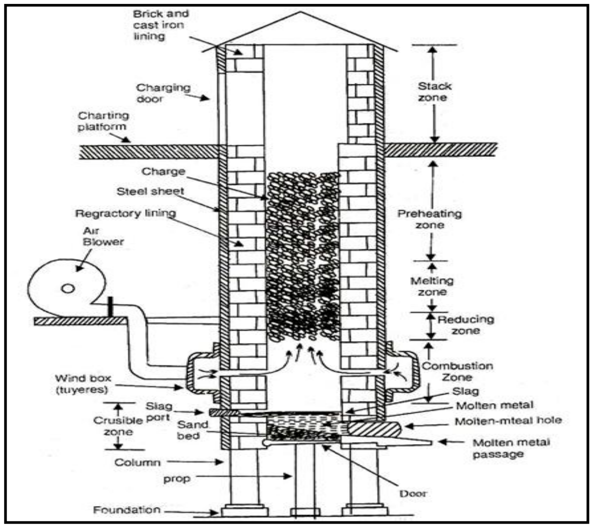


Figure 1 : Conventional cupola

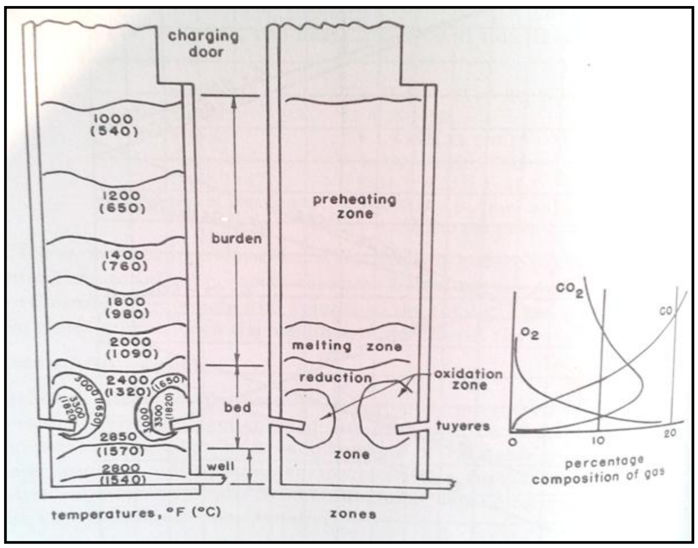


Figure 2 : Systematic combustion condition in cupola

In the cupola, heat for melting is generated by the combustion of carbon in coke to CO_2 and CO mixtures as the air blast penetrates the cupola and reacts with the hot coke. As the gases penetrate the coke bed, oxygen is progressively depleted, along with the formation of CO_2, and a zone of maximum temperature up to 1650 to 1705 ^{0}C is created. As the gas high in CO_2 moves up through the excess coke, some of the CO_2 reacts with C endothermally to form CO. The top effluent gas yields 10 to 14% CO_2 and 15 to 10% CO, Higher CO_2 in the effluent gas and CO in the lower side indicates a more oxidizing condition from excess blowing or a minimum coke percentage of reactivity. This will give higher melting rate, but will produce lower iron temperature, less carbon pickup, and more oxidation of silicon. Effluent gas higher in CO and lower in CO_2 indicates a less oxidizing condition from more coke or less blowing, causes less melting rate, higher iron temperature, low silicon loss and higher carbon pick up. Preparation of coke bed is vital to the initial start of the melt and a bed height of 40 to 60" above the tuyeres to the charging door is to be maintained, by experience and based on blast volume, cupola diameter and desired melting rate. With higher bed, melting occurs higher in the stack, slower and hotter with less oxidation and more carbon pick up. A low bed melts lower, faster, and colder with more oxidation. There is preheat zone in the upper stack, where metal charge is preheated progressively by the ascending hot gases as the metal descends into the melting zone. Melting zone is located 20” to 50” above the tuyeres, where maximum temperature is generated and the metal melts. Well zone collects the melted metal and slag as it drips through the coke, accumulates in the well and goes to the tap hole. There are several chemical zones in the cupola, (i) the zone immediately out from the tuyeres is very oxidizing. (ii) The hottest melting zone where more CO_2 exists is slightly oxidizing and (iii) A reducing zone is in the upper melting and preheat zones where coke and CO exist. Air for combustion of coke is introduced through tuyeres equally spaced around the cupola, the number and size is dependent on the size of the cupola for proper air volume, pressure, and velocity. Total tuyeres area ranges between 3 to 10% of cupola area for optimum air velocity for penetration and combustion efficiently. Blowers are supplying air, fan of centrifugal type. The air required to melt 900 kg. (I Ton) of iron is 620 to 680 m^3 (22000 to 24000 ft^3) STP or 770 to 835 kg. (1700 to 1840 lb). Air from the blower is transmitted into the tuyeres through a duct system and wind box. Back pressure ranges from 3.3 or 8.5 N or more, depending on charge density and stack height. Standard cupolas are available in 15 sizes is, 23” (ID), 1–2 ton h^{-1}. to 84” (ID), 30–32 tons h^{-1} Capacity.

Air requirements: The weight[4] of air supplied to the cupola is approximately equal to the weight of metal charged.378 cu.ft. (NTP) of O_2 combined with 12 lb. of carbon for complete combustion with air to produce 378 cu.ft. (N.T.P) of carbon dioxide.

Air contains 21% O_2, so 1800 cu. ft of air is required. So, composition of the gas from complete combustion with air would be 378 cu ft of CO_2 and 1422 cu ft of N_2

or $378 \times 100 / (1422 + 378) = 21\%\ CO_2$

But it is impossible to obtain complete conversion of O_2 to CO_2. If all 378 cu ft of CO_2 were reduced, 2 times or 756 cu ft of CO. would result. The composition of effluent gas would be

$$756 \times 100 / (1422 + 756) = 34.7\%\ CO$$

In practice, both; CO_2 and CO are always present. When the CO_2 is known in the effluent gas, then CO content can be calculated.

$$\%\ CO = 34.7 / 21.0 \times (21 - \%CO_2) = (1.652)\ (21 - \%\ CO_2)$$

So N_2 content can be calculated.

$$\%\ N_2 = 100 - (\%CO_2 + \%CO)$$

Assuming no oxygen, volatile impurities or other sources of CO and CO_2, it is possible to obtain complete gas analysis. But in actual practice, the decomposition of limestone (added as a flux to eliminate impurities producing slag) liberates CO_2, part of which may react with carbon to yield CO. If the limestone addition is 25% of the carbon content of the coke, the relation between CO_2 and CO is % CO = (1.682) (21.28 - % CO_2). Similarly, decomposition of water vapor produces one volume of CO from each volume of water vapor in the air blast. Likewise, any volatile matter in the fuel releases volatile products and dilute the effluent gas. Based upon the measured composition of the effluent gases, metal to fuel ratio and melting rate, air requirements may be calculated as follows.

Air requirements (Theoretical at N.T.P)

= (Cu. ft. of air / lb. carbon) (lb. carbon / Ton of iron) x (Tons iron min^{-1})

If effluent gas contains 12% CO_2, the melting rate is 12 tons h^{-1}. and the metal: fuel ratio is 10:1, using coke containing 90% carbon, then the air requirement are (109.1) (200)(0.9)(12/60)

= 3940 cu ft (N.T, P)

If an air loss between meter and tuyeres is 5%, the metered air is 3940 × 105/100 = 4140

If the actual conditions of metering are 80^0F and 29.3 in Hg. Pressure, the volume metered can be calculated using correction factors:

$$(4140) \left(\frac{0.946}{0.911}\right)\left(\frac{1}{0.979}\right) = 4430 \text{ cu. ft. at } 80°\text{ F and } 29.3 - \text{in Hg pressure}$$

Reasons for once popularity: Cupola was the predominant furnace for iron melting because of its simplicity and low cost of melting. A cupola can accept [3] a wide range of raw materials including oily, wet and contaminated scrap, which are unsuitable for an electric furnace for safety reasons and because of the contamination, their use is limited for metallurgical reasons.

Inherent technical problems:

- Pollution - SPM, SO_x, etc.
- Composition maintenance- Not homogeneous.
- Competitors- Arc & induction furnaces.

Problems with competitors:

- Threat to national energy security
- Pollution at power generating plant

In the domain of Indian foundries, about 4500 units are mainly dependent on electric energy to produce about 10 million tons castings per annum. Indian foundries are planning to produce 20 million tons of casting by 2020 and 30 million tons by 2030. Scenario of energy share for generation of electricity [15].

Table 1. Indian scenario of electricity production

Fuel	MW	% age
Total thermal	**198,484**	**69.8**
Coal	173,018	60.9
Gas	24,473	8.6
Oil	994	0.3
Hydro (Renewable)	42,623	15.0
Nuclear	5,780	2.0
REST** (MNRE)	37,415	13.2
Total	**284303**	

India having 7.1% of world coal reserve, ranks 3rd in position for its consumption in the world after China and America. At this rate of consumption, Indian coal reserve is estimated to deplete completely within next 114 years. In iron melting process, 40-50% of input energy is consumed to melt the metal and 50-60% is going wasteful. An attempt has been made to reduce the present emission level of SO_x by replacing coke partially or fully with biofuel (Rice husk) as well as bio waste utilization.

Technical Difficulties with objective:

- Low C.V.
- High V.M. (1% - coke) → In DBC, supply of additional air in upper tuyeres may be applied.

Details of rice husk: Paddy rice [16] as one staple food for over 50 percentage of the world population is cultivated by over 20% of world population and covered 1 percent of the earth's surface. The global paddy rice production had been increasing continuously on an average rate of 16.48 million tons in the last 10 years, with the production of 2011 around 718.3 million tons, valuing around 240 billion US dollar. The main paddy rice producing countries are China, Egypt and Cuba, which contributes to 27.51%, 0.63% and 0.77%, respectively of the global paddy rice production. Paddy rice on an average consisted 72 % of rice, 5-8 % of bran, and 20-22% of husk. India produces 120 million tones paddy and 24 million tones of rice husk per year.

Rice husk from mill →Sieving→ Grinding→ Palletizing with high pressure

Table: 2. Fuel Analysis

Results of analysis	Moisture (%)	V.M. (%)	Ash (%)	Fixed Carbon (%)	Gross C.V. Kcal/Kg	Bulk density gm/ml.	C (%)	H (%)	S (%)	N (%)	O (%)
Coke	1.23	0.58	12.39	87.03	6647	1.06	64.49	2.29	0.42	1.48	10.61
Rice husk	9.62	60.54	15.35	24.11	3540	0.35	68.47	5.27	0.096	0.43	5.39

RESULTS AND DISCUSSION

Mathematical modeling

Heat Balance [4]: The main purpose of a cupola is to burn coke to provide heat for the melting of iron. Heat is developed from different sources in addition to coke, i.e. from the oxidation of silicon and manganese. In addition to melting, heat is required to calcine limestone, form and melt a slag, to provide radiation losses. The calculation of heat values in a cupola is based on the laws of thermo chemistry and thermo dynamics.

Table 3: Operational data For 23 inches (ID) Cupola

S. No.	Operating data	Data	S. No.	Operating data	Data
1	Metal: Kg.	2100	13	Temperature in Iron degree C	30
2	Coke	200	14	Fixed carbon,coke	87.03
3	Coke + Rice husk briq.	90+168	15	Fixed carbon, rice husk briquette	24.11
4	Limestone	60	16	Coke ash	12.39
5	Si in charge,%	2.22	17	rice husk briquette ash %	15.35
6	Si in melt %	2.03	18	C.V., Coke, KCL	6647
7	Mn in charge,%	0.67	19	C.V, rice husk briquette KCL	3540
8.	Mn in melt	0.45	20	Temperature of flue gas ^0C	450
9	Carbon in charge,%	4.08	21	CaO in slag,%	15.6
10	Carbon in melt,%	4.01	22	Blast rate, cfm/m	1500
11	FeO in slag,%	11.54	23	sp.heat of slag, KJ/Kg./ ^0C	1.34
12	Average temperature in melt ^0C	1410	24	Blast tem, ^0C	15.5

Table 4: Heat input and Heat Output - With coke

S. No.	Heat input	Unit/h KJ/h
1	Potential heat of fuel:	5556892 kJ
		5556892 kJ
2	Net potential heat of fuel	4458572.3
3	Fe Oxidation	87522.69
4	Si Oxidation	55240.67
5	Mn Oxidation	14671.32
6	Sensible heat in blast	228653.6
7	**Total (Heat input)**	**4844661 KJ**

S. No.	Heat output	Unit/hr KJ/hr
1	Heating, melting and Superheating of iron	2728994
2	Calcining of Lime stone	100917.9
3	Formation, Heating and superheating of slag	356354.7
4	Decomposition of moisture in blast	251143.7
5	Sensible heat in the in stack gas	611421
6	**Total (Heat output)**	**4048831.3**
7	**Radiation loss (Heat input-Heat output)**	**795829.7**
8	**Radiation loss in %**	**16.42693**

Table 5: Heat input and Heat Output- With 50% equivalent rice husk briquette

S. No.	Heat input	Unit/hr KJ/hr
1	Potential heat of fuel:	4986531kJ
		4986531KJ
2	Net potential heat of fuel	4158318
3	Fe Oxidation	59363.22
4	Si Oxidation	95944.325
5	Mn Oxidation	20673.22
6	Sensible heat in blast	135556.4
7	**Total (Heat input)**	**4469855.16**

S. No.	Heat output	Unit/hr Kj/hr
1	Heating, melting and Superheating of iron	2736750
2	Calcining of Lime stone	100917.9
3	Formation, Heating and superheating of slag	234399.4
4	Decomposition of moisture in blast	99259.68
5	Sensible heat in the in stack gas	362478.5
6	**Total (Heat output)**	**3533805.48**
7	**Radiation loss (Heat input-Heat output)**	**936049.16**
8	**Radiation loss in %**	**20.94138**

Table 6: Balance sheet of Sulphur in cast iron in cupola h^{-1}

		PIG	FIR	MS	COKE	Rice husk	Total	%
1 (with coke)	**Kg.**	1200	840	60	200			
	S%	0.03	0.066	0.04	0.42			
	S	0.36	0.5544	0.024	0.84		1.7784	
2 (with Rice husk)	**Kg.**	1200	840	60	90	168		
	S%	0.03	0.066	0.04	0.42	0.096		
	S	0.36	0.5544	0.024	0.378	0.16128	1.47768	
	Reduction In charge						0.30072	**16.90958**
						coke	**50% eq. rice husk**	
	Reduction in experiment					180.17	138.5	**23.12816**

It was observed that sulphur was reduced by 17% with 50% equivalent rice husk briquette, which is good agreement to experimental value of 23%.

APPLICATIONS

The use of rice husk in combination with coke in cupola produce energy and gives better results than coke. Greener perspective of this project, which could be achieved up to certain extent.

CONCLUSIONS

In the present investigation, we have used rice husk in combination with coke in cupola to produce energy. The observations reflect better results for combination of rice husk with coke in different composition than coke. Greener perspective of this project, which could be achieved up to certain extent are -

- If we see the technical impact, it clearly shows less emission of SO_x, which helps in reducing pollution.
- Commercial aspect is very important and use of rice husk with coke will reduce the cost of material as well as production process.
- Waste management is a big challenge in the present scenario and use of biowaste like rice husk for energy generation will explore its uses in more fields.
- Less GHG gas emission is also an important outcome of the present investigation.

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