Centre For Pyrometallurgy

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Pyrometallurgy

The Center for Pyrometallurgy is established under Institute of Eminence Scheme of IIT Madras in 2021. Pyrometallurgy is the physical chemistry and process technology of the production of metals and alloys from ores and minerals by high temperature techniques and may therefore be considered as a specialized hybrid of science and engineering within the overall discipline of materials science and engineering. The objective of this unique center would be to impart training, education and industrial consultancies in the much needed area of pyrometallurgical route based metal production and refining. The majority of R&D work will be pre-competitive in nature and is aimed at solving common problems of industries – such as optimization and control of large scale production reactors involved in ferrous and non-ferrous extraction and refining of metals, process modelling, sintering and reducibility of low grade ores, waste recycling and utilization, steel cleanliness, ferro-alloy production, copper smelting, recovery of precious metals and rare earths from slags, anode muds and so on. The research projects will be conducted in close collaboration with metallurgical industries of common interest. The activities of the center will be governed by the consortium of industries/companies who will jointly fund this center. The Center is proposed to have a consortium of industry partners and R&D institutions of repute who are involved in the Ferrous/Non-Ferrous pyrometallurgy-based research and process development activities to produce metals in a sustainable manner. Potential Industry/R&D Partners are invited to collaborate with this center.

International Advisory Committee of Centre For Pyro Metallurgy, I.I.T Madras

1. *Prof. David Robertson, Professor Emeritus of Metallurgical Engineering, Missouri S & T USA.*
2. *Prof. Seshadri Seetharaman, Professor Emeritus Royal Institute of Technology, Stockholm, Sweden.*
3. *Prof. Rauf Hurman Eric, Chamber of Mines Professor, University of the Witwatersrand , South Africa.*
4. *Prof. B.K Mishra, Director IIT Goa, Former Director CSIR-IMMT Bhubaneswar, India*
5. *Prof. Geoffrey Brooks, Director of Research, Swinburne University of Technology, Australia*
6. *Prof. Paulo Santos Assis, School of Mines, Federal University of Ouro Preto (UFOP), Brazil.*
7. *Prof. Olena Volkova, Director, Institute of Iron and Steel, T U Bergakademie, Freiberg, Germany.*
8. *Prof. Johannes Schenk, Head of Chair of Ferrous Metallurgy, Montanuniversitaet Leoben, Austria*

Dr. Amit Bhalla
Co-ordinator, Centre for Pyrometallurgy, IIT Madras
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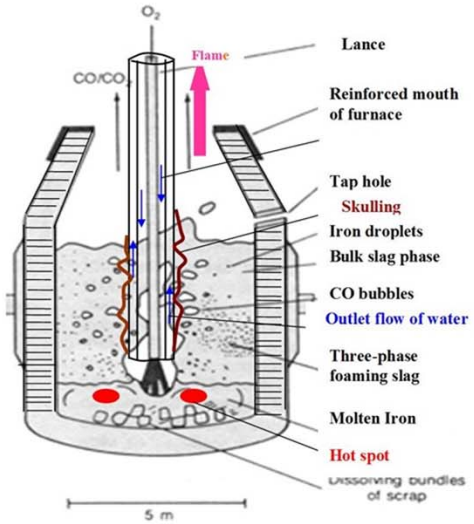
Projects Executed/Ongoing so far

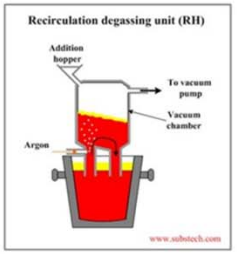
1. Expert model of BOF Steelmaking Process
2. Physical and Mathematical Modeling of RH Degassing Process
3. Physical and Mathematical Modeling of Dry Slag Granulation Process
4. Data Based Modeling Approach to Control Iron and Steelmaking Process employing AI/ML tools.
5. Optimization of Steel Plant Supply Chain using Innovative AI techniques
6. Mathematical Modeling of COREX Iron-making Process and its Industrial Validation
7. Heat Transfer and Fluid Flow Modeling of Twin-Roll Casting Process
8. Mathematical Modeling of MIDREX Iron-making Process and its Industrial Validation
9. Microwave assisted beneficiation of lean quality iron ores
10. Modeling of pulverized coal injection in modern blast furnace.
11. The reducibilty of chromite ore and reactivity of carbonaceous reductants.
12. The kinetic study of reduction of manganese ore using hydrocarbons.

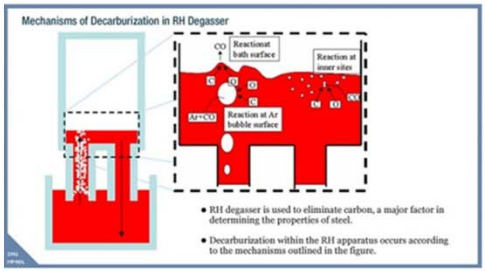
Basic Oxygen Steelmaking process

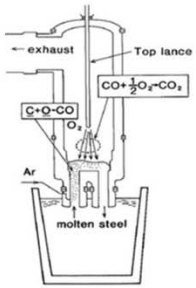


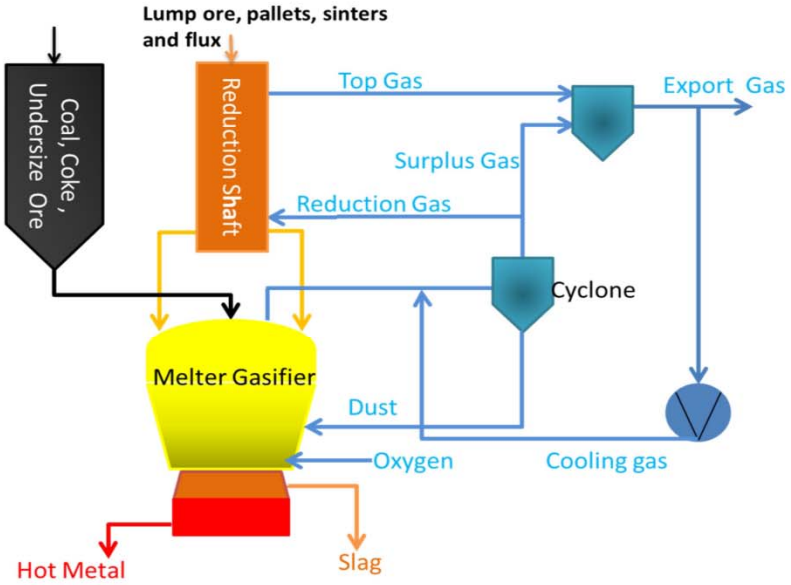
Physical state of the Basic Oxygen Steelmaking Process in the middle of the blow

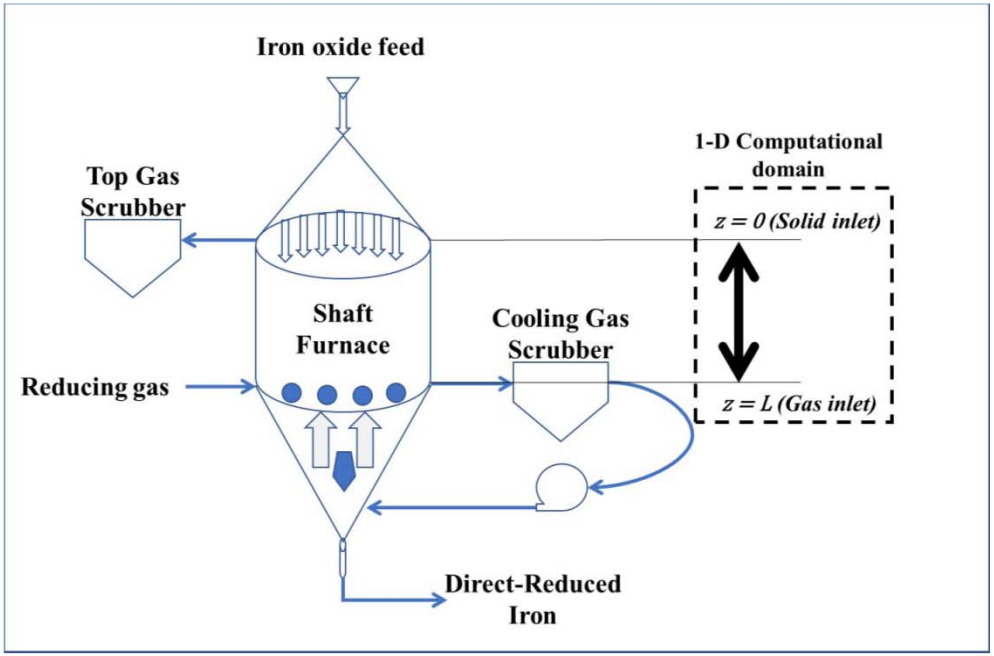
THE RH PROCESS











The basis for analysis of all chemical and metallurgical processes is the mass and energy balance coupled with the understanding of thermodynamics and kinetic constraints of the process. Plant design, capital costs, and technical evaluations are all dependent on such calculations.

High temperature metal extraction processes involve:

- **Heating, melting and dissolution of raw materials and fluxes**
- **Dynamic interaction between slag, metal, solid and gas phases existing all together at very high temperatures.**
- **Reaction chemistry of the process which involves thermodynamics and kinetics (most importantly the dissolution rates of the solid charged materials like scrap, lime, other fluxes etc).**
- **The Computational Fluid Dynamics (involving diffusion, fluid flow, heat transfer to estimate the concentration, temperature, velocity and pressure variation within the reactor).**
- **Requires multi-disciplinary understanding of high temperature metallurgy, mathematics, computational approaches, tools and techniques**

Integrated reactor approach

Slag-Metal reaction: Multiphase multicomponent mixed transport

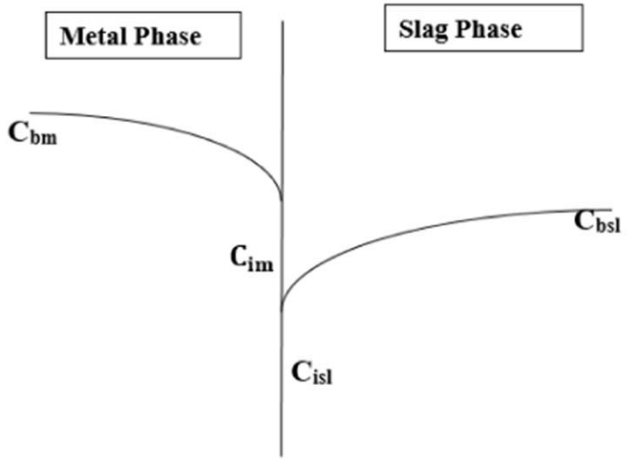


Figure A1. Composition profiles in metal and slag.

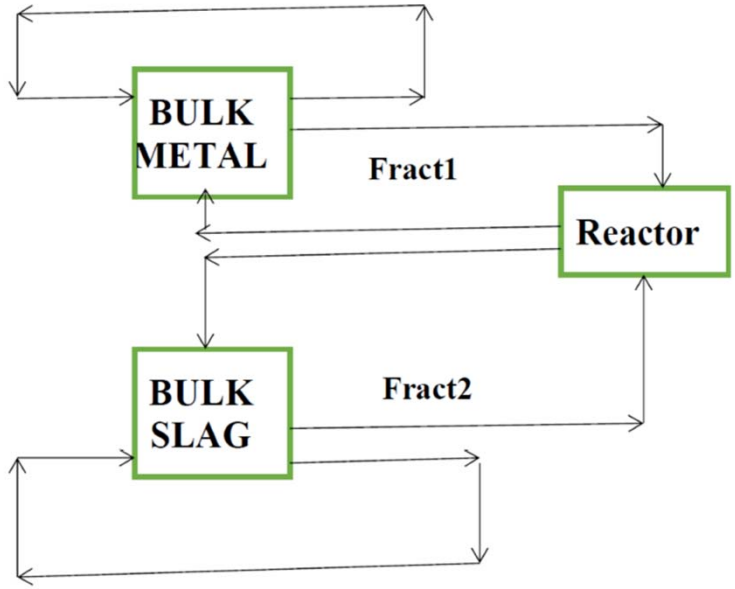


Figure A2. Interaction of different modules.

$$k_m \cdot A \cdot (C_{bm} - C_{im}) = -V_m \cdot (dC_{bm}/dt) \quad \text{(A1)}$$

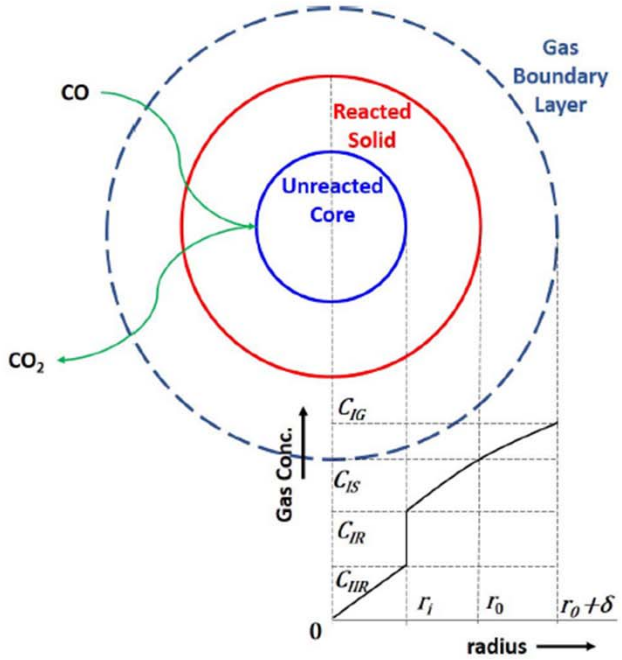
$$k_{sl} \cdot A \cdot (C_{bsl} - C_{isl}) = -V_{sl} \cdot (dC_{bsl}/dt) \quad \text{(A2)}$$

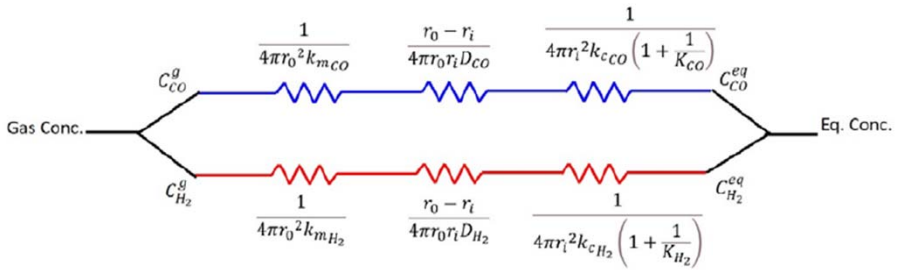
$$(k_m \cdot A \cdot dt/V_m) = -dC_{bm}/(C_{bm} - C_{im}) = \text{Fract1} \quad \text{(A3)}$$

$$(k_{sl} \cdot A \cdot dt/V_{sl}) = -dC_{bsl}/(C_{bsl} - C_{isl}) = \text{Fract2} \quad \text{(A4)}$$

Metals **2022**, *12*, 638. https://doi.org/10.3390/met12040638

Gas-Solid reaction: Coupled diffusion assisted mass transport/chemical reaction control





$$FeO + CO = Fe + CO_2 \qquad \text{(A.1)}$$

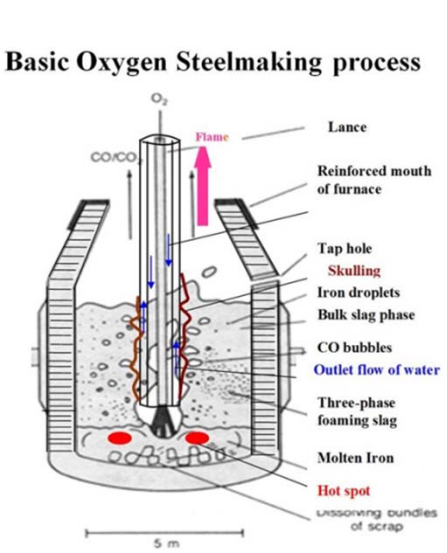
$$\dot{n}_I = \frac{C_{IG}-C_{IS}}{\frac{1}{4\pi r_0^2 k_m}} = \frac{C_{IS}-C_{IR}}{\frac{(r_0-r_i)}{4\pi r_0 r_i D_{gas}}} = \frac{C_{IR}-\frac{C_{IIR}}{K_{eq}}}{\frac{1}{4\pi r_i^2 k_c}} \qquad \text{(A.2)}$$

$$\dot{n}_I = \frac{C_{IG}-C_{Ie}}{\frac{1}{4\pi r_0^2 k_m}+\frac{(r_0-r_i)}{4\pi r_0 r_i D_{gas}}+\frac{1}{4\pi r_i^2 k_c\left(1+\frac{1}{K_{eq}}\right)}} \qquad \text{(A.3)}$$

$$frac = \frac{N'}{Q_{gas}\left[\frac{1}{4\pi r_0^2 k_m}+\frac{(r_0-r_i)}{4\pi r_0 r_i D_{gas}}+\frac{1}{4\pi r_i^2 k_c\left(1+\frac{1}{K_{eq}}\right)}\right]} \qquad \text{(A.7)}$$

Where, $N' = Q_{gas} n_p \Delta t$

$$avg.frac = \frac{1}{r_0}\int_0^{r_0} frac\,.\,dr \qquad \text{(A.8)}$$



Physical state of the Basic Oxygen Steelmaking Process in the middle of the blow

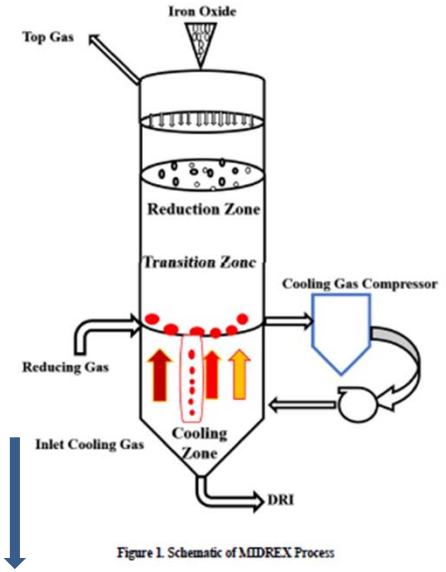


Figure 1. Schematic of MIDREX Process

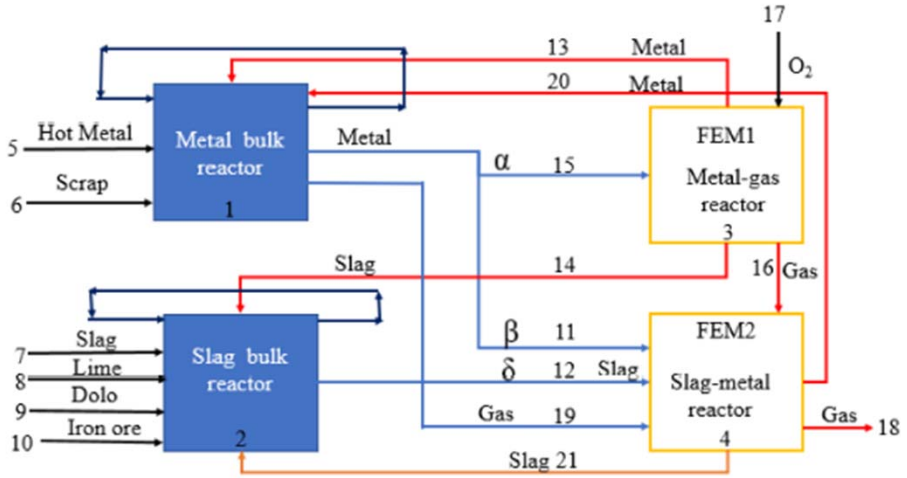
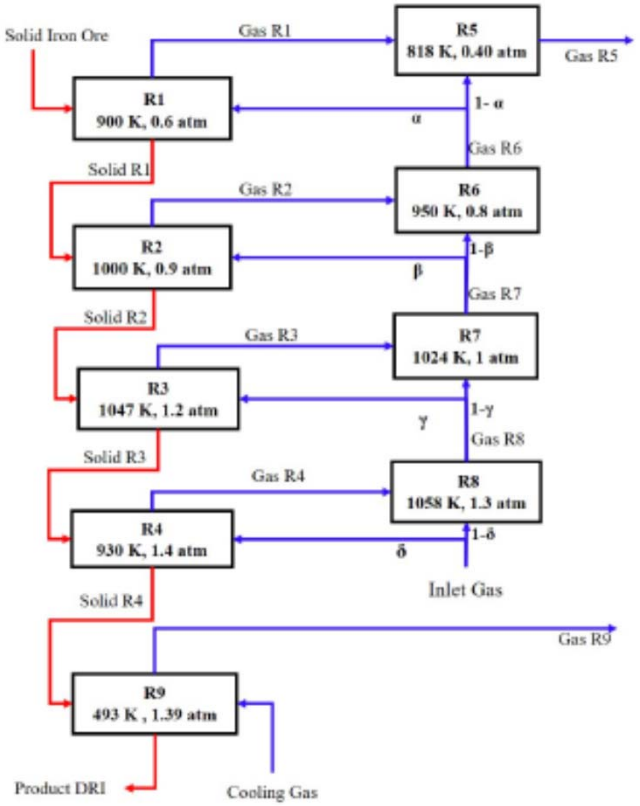
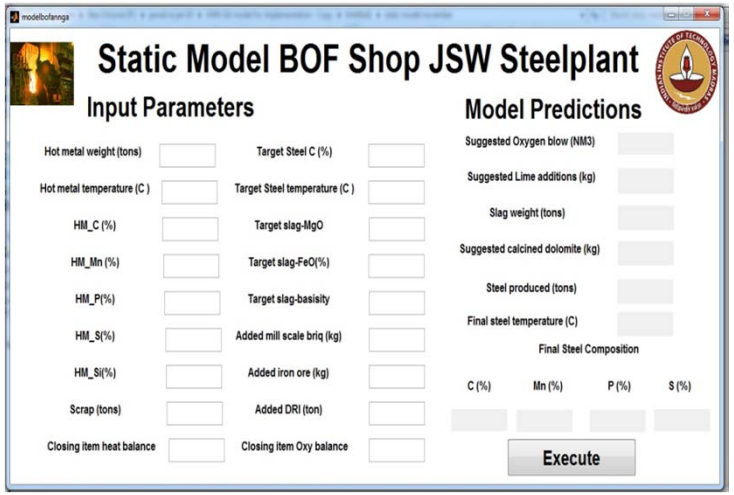


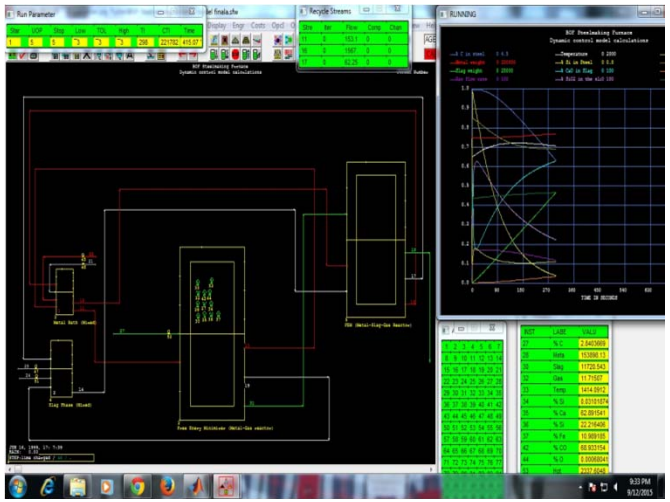
Figure 1. Flowsheet of multiple-reactor-based BOF steel-making process.

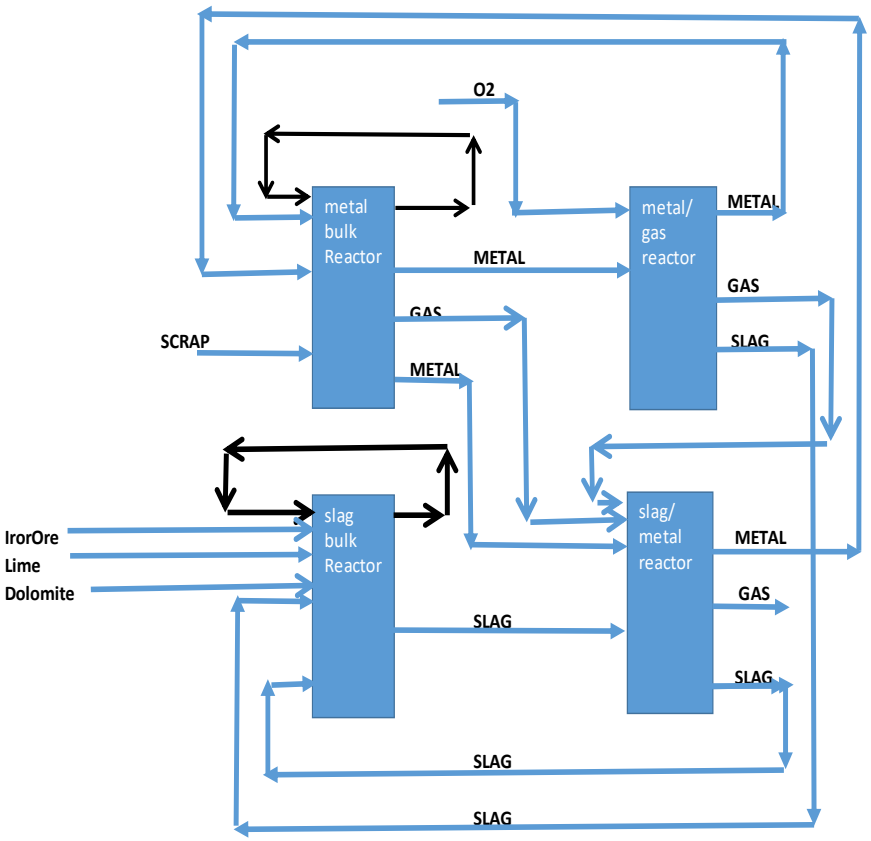


Computational Expertise of the group

- *Thermodynamic/Kinetics based models using **FactSage-Macro-programming***
- *AI/ML/Data based modelling using **MATLAB/Python***
- *Flow-sheet based reactor modeling using **METSIM/ChemSheet/PyroSim***
- ***Excel Solver/VBA** based models*

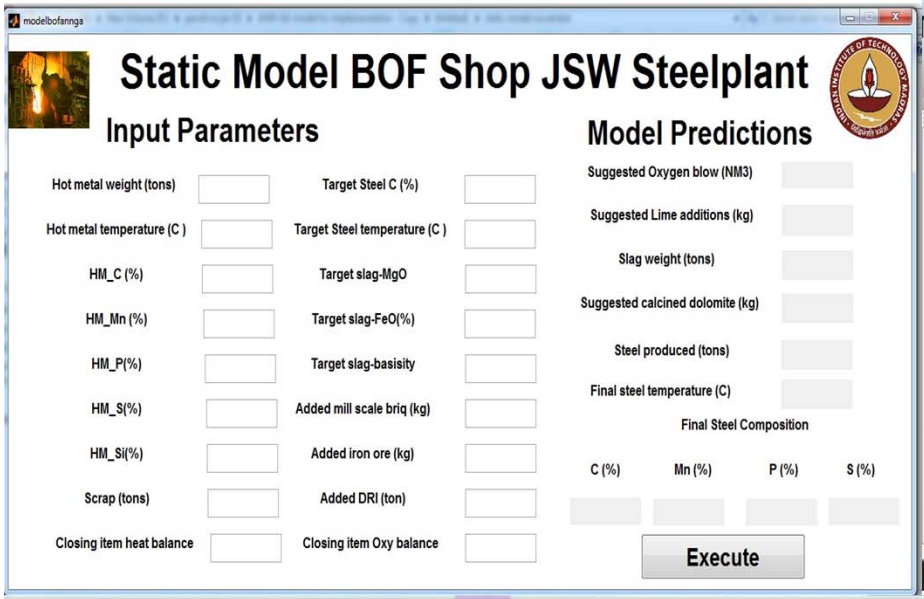


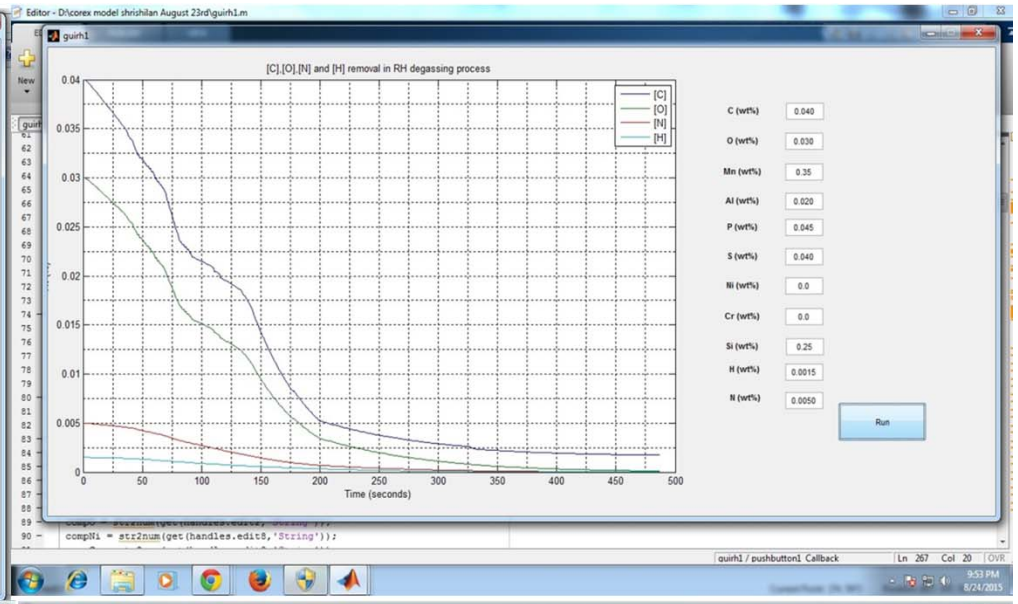


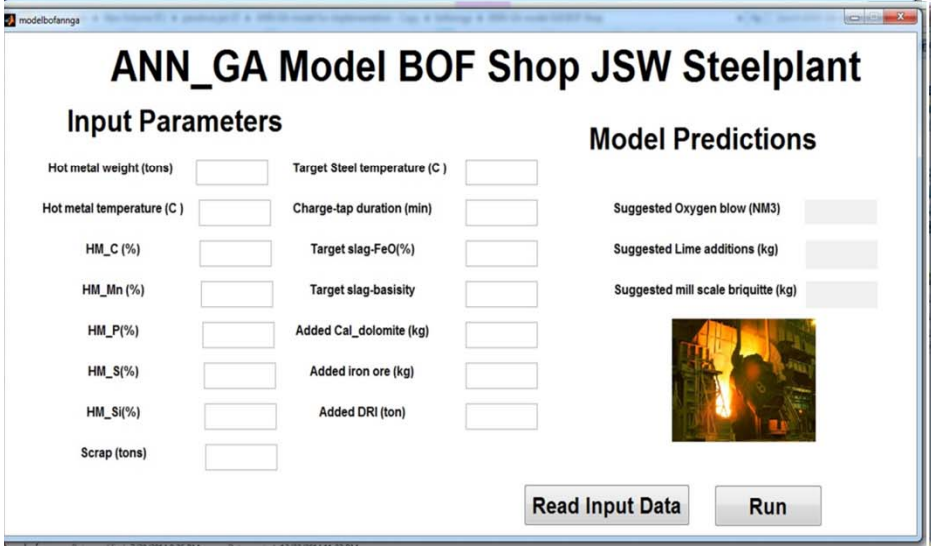


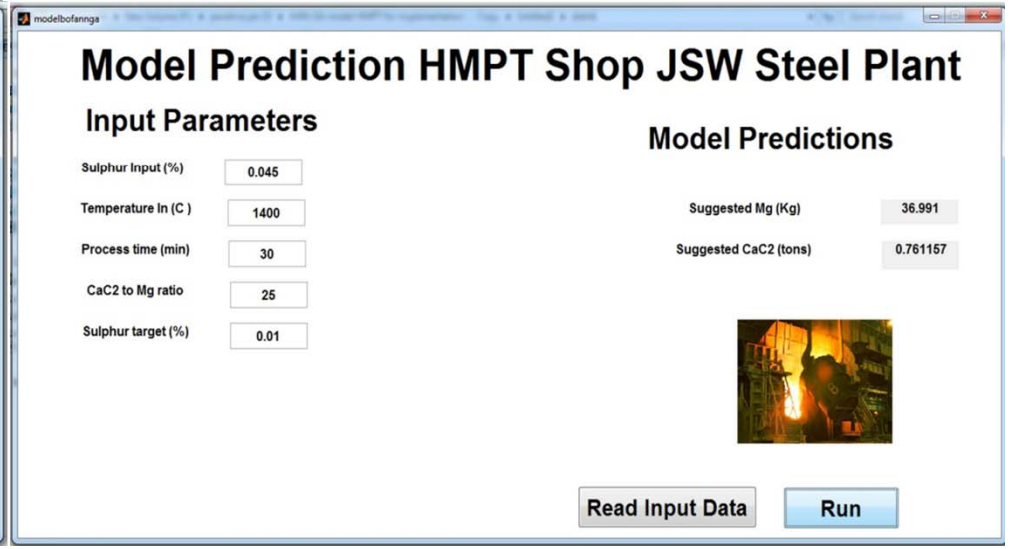
FLOW SHEET OF MULTIPLE REACTOR BASED OF BOF STEELMAKING PROCESS

GUI Snapshots…

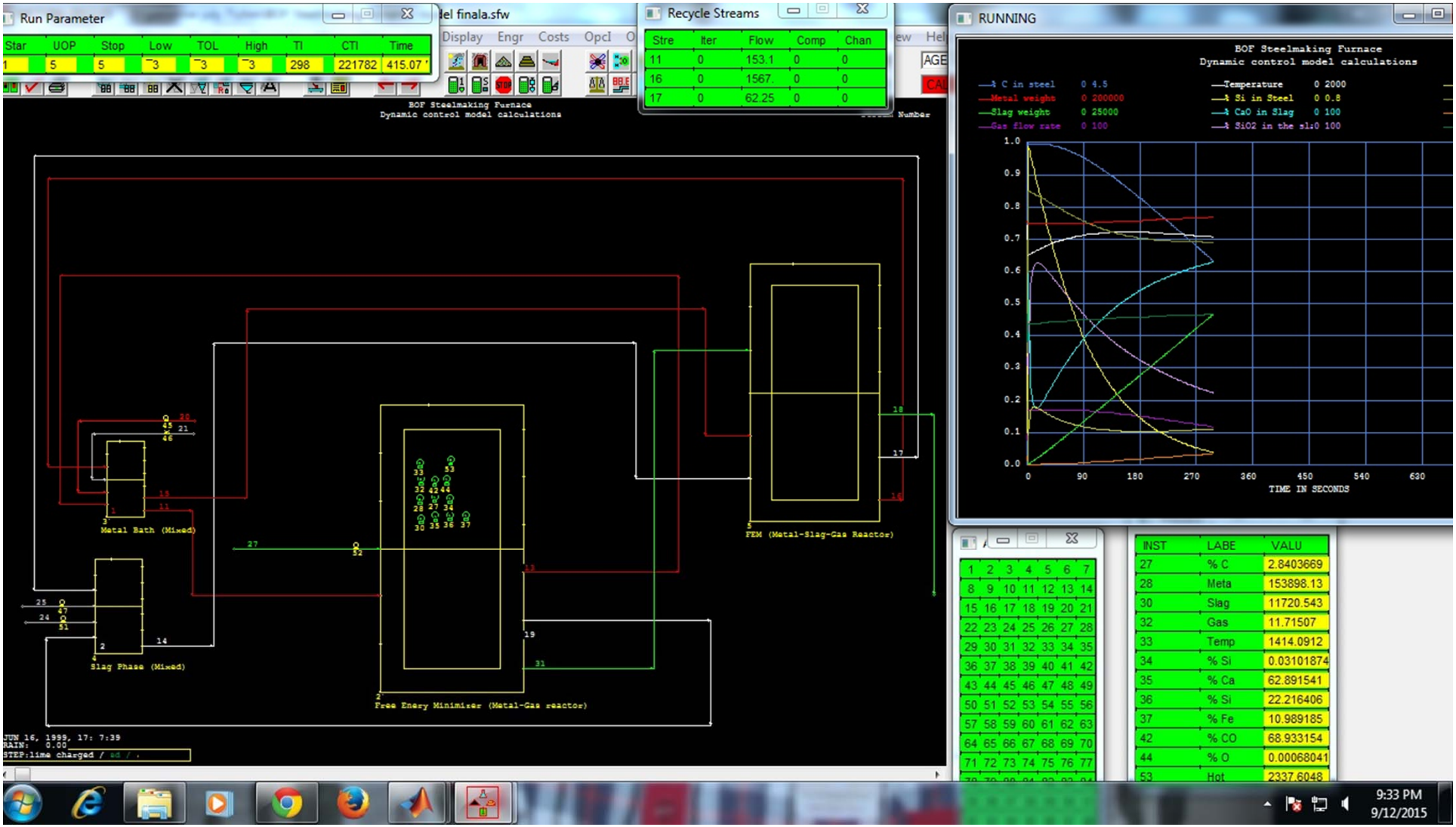








Virtual Simulation Laboratory



Center for Pyrometallurgy—IIT Madras

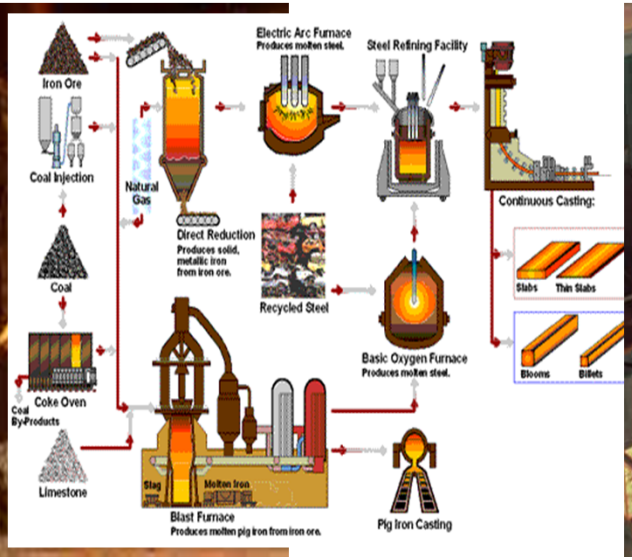
The production of iron and steel and non-ferrous metals by pyrometallurgical processes is an important and essential requirement. Pyrometallurgy is a specialised field that is critically important for the production of metals and alloys. Given the important need to reduce and minimize greenhouse gas emissions the technological focus of future pyrometallurgical R&D by universities and industry alike must concentrate on sustainability issues such as improved energy efficiency, recycling and waste minimization. Continued efforts are also needed on process optimization and new process development with a view to reducing capital and operating costs of the new large upcoming plants. Using the academic and industrial collaborations, there was a need to establish the "center for pyrometallurgy" research and development in order to solve the sustainability related issues in pryometallurgical route based metal extraction and recycling processes.

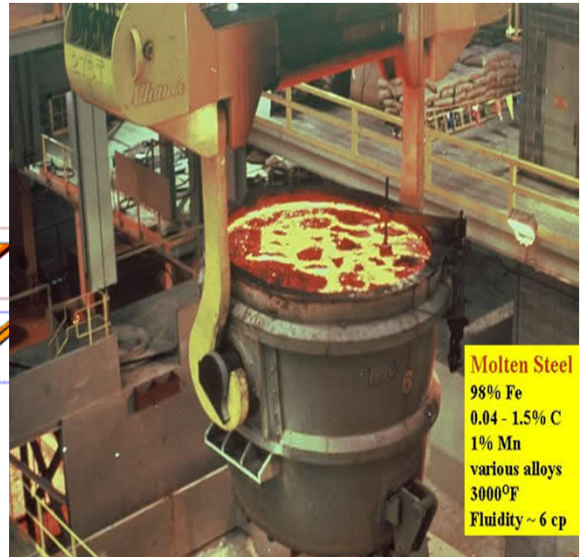
Center for Pyrometallurgy—IIT Madras

The main functional areas of the Center will include the following:

I. Applied research involving process modelling in association with steel/metal/mineral industries

II. Fundamental research





I. Applied research involving process modelling in association with steel/metal/mineral industries

Optimization and control of industrial iron and steelmaking processes and other metal extraction processes require a well defined methodology which involves comprehensive modeling efforts. It includes application of **computational thermodynamics and computational fluid dynamics** along with advanced optimization techniques like **Artificial Intelligence** and **Genetic Algorithms**. The **data driven modeling techniques** which are based upon multivariate analysis and Artificial Neural Networks are also used in conjunction of these. The objective is to develop a group which is competent enough to provide expertise in the area of control of complex industrial problems related to various metal extraction and steel industries. It will involve very active collaboration and interaction with metal and steel industries in terms of potential projects, student exchange and training programs. This group will demonstrate its capability in following possible areas:

- **Development of level-2 automation control systems for iron and steelmaking processes.**
- **Trouble-shooting in industry operations.**
- **Inclusion Engineering and clean steelmaking.**
- **Design of suitable mold powder for high speed continuous casting process and development of mathematical model to estimate heat transfer coefficient in continuous casting molds.**
- **Sustainable production of important non-ferrous metals (like Aluminum, Magnesium, Titanium, Copper, Zinc and Nickel) will also be investigated under this center by pyrometallurgy route.**
- **The important projects will also include the recycling and utilization of waste materials like electronic wastes recycling to recover precious metals in smelters, pyrometallurgy route based recovery of rare earth metals from red mud, reduction roasting and beneficiation of lean quality ores, recycling of Li-ion batteries through pyro metallurgy route are some of the strategic projects which may be undertaken in this center.**

II. Fundamental research

Fundamental studies based upon thermodynamics and computational fluid dynamics.

Most of the high temperature processes are close to thermodynamic equilibrium if there is adequate mixing. The mixing aspects of the reactors can be studied with the help of CFD models as well as laboratory based cold model experiments. For thermodynamic studies, FactSage based studies would be done. For non-equilibrium reactors, the application of FactSage/MetSim would be useful where a non-equilibrium reactor is defined as a combination of large number of inter-connected equilibrium reactors constrained by limited flow of materials among them. It is possible to study following processes:

- Mixing in the steel ladle, tundish and continuous casting molds.
- **Thermodynamics and kinetics based modeling of BOF/EAF/LF/VAD/VOD/AOD steelmaking processes.**
- **Desulphurization and degassing during secondary steelmaking**
- Design of nozzles applied to steelmaking process
- **Slag/Metal equilibrium studies**
- **Clean steel production/Inclusion control during ladle metallurgy**
- **Thermodynamic and kinetics based modeling of ferro alloy production**
- **Mathematical modeling of Blast furnace/Alternate iron-making with new additions of raw materials and recycling possibilities**
- Thermodynamics based modeling of non-ferrous extraction (Copper smelting, Ilmenite smelting etc.)

- **Expected deliverables of the center**

- A world class "Centre of Pyro-metallurgy" is proposed to be established **with high temperature equipment and facilities along with a vibrant consortium of industry partners along with global engagements and exchange programs (Joint Degree /Supervision programs and so on).**
- **Consultancy, Industry sponsored joint training programs/courses/workshops**
- **Generation of IPR** outcomes in terms of good number of **publications in high impact journals**, filing of **patents**, potential **Masters and Ph.D students** who are employable by leading industries and academic institutions.
- The **joint industry sponsored masters/doctoral programs** will be developed in the specific and much needed area of pyrometallurgy. There would be lot of exchange visits of students and faculty members across global institutes of repute to solve this purpose.
- The center would be known for **solving national issues related to the production of metals by pyrometallurgy route in a sustainable manner related to raw material, energy and environment.**

D. Research Facilities in "Center for Pyrometallurgy"

The following facilities are supposed to be the part of this center.

Equipment: (all facilities need not to be located in IIT Madras, some may be outsourced or created at industry site as per the situation)

1. High temperature furnaces (Muffle, Tubular, Induction) with or without controlled atmosphere up-to 1600 °C.
2. Facilities for material pre-treatment and sample preparation: jaw breaker, vibration sieving machine, disc mill, ball mill, mixer, pellet mill, hard metal saw etc.
3. Electrically heated rotary furnaces (large and small) for the pre-treatment of metal containing raw materials in the temperature range up to 1200 °C (large) and 1400 °C(small), respectively
4. Cold pressing machines
5. CO/H2 gas analyzer
6. High temperature viscometer for viscosity estimation of slag and glass
7. DHTT/SHTT (Double and single hot tip thermocouple to study crystallization behavior of slags)
8. High temperature furnace for smelting or sintering of metals with high melting point or refractory materials in the temperature range up to 1750 °C
9. Magnetic separators
10. High temperature TGA
11. Vacuum induction furnace
12. Characterization facilities –XRD/SEM (already existing in the department)
13. Confocal Laser Scanning microscope (CLSM) at 1700 °C
14. High Quality Metal Quality Analyzer (ASPEX)—for inclusion mapping
15. Pilot scale experimental facilities

Software:

MATLAB	existing
Fluent	existing
COMSOL	existing
FactSage (only ferrous metallurgy data base)	existing
Fortran/C++/Java	existing
FlowBal	existing
METSIM	2 user license
ChemSheet	1 user license
PyroSim	existing

Process Metallurgy Lab

Video available at the following Youtube link:

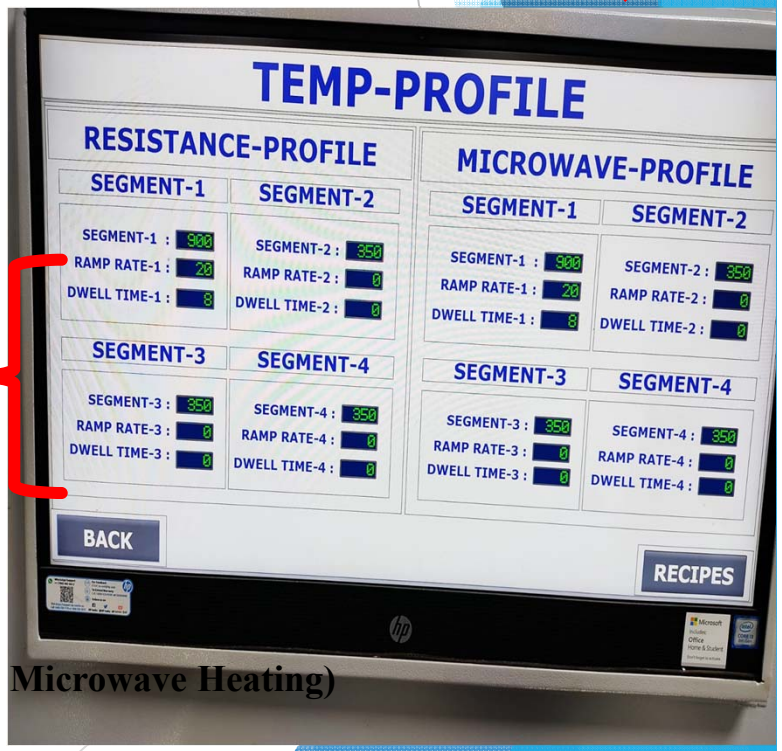
https://www.youtube.com/@centerforpyrometallurgy-ii1768

Experimental Facilities

- High temperature Hybrid Microwave heating furnace (1700°C)
- High temperature controlled atmosphere Vertical Tubular furnace (TGA assisted) (1700° C)
- Gas Analyzer (CO, CO2, H2, O2, and CH4)
- CO Generator tubular furnace
- 5 Kg jar mill
- Sieve analyzer
- 20 Tons Cold pressing machine
- Magnetic separators (WHIMS, Davis tube)
- High temperature controlled atmosphere Horizontal furnace
- Muffle furnace (1700°C)
- Induction tilt furnace for melting of steel and slag
- Induction Rotating Cylinder Furnace along with Motor, Gear Box

Hybrid Microwave Furnace

Control Panel

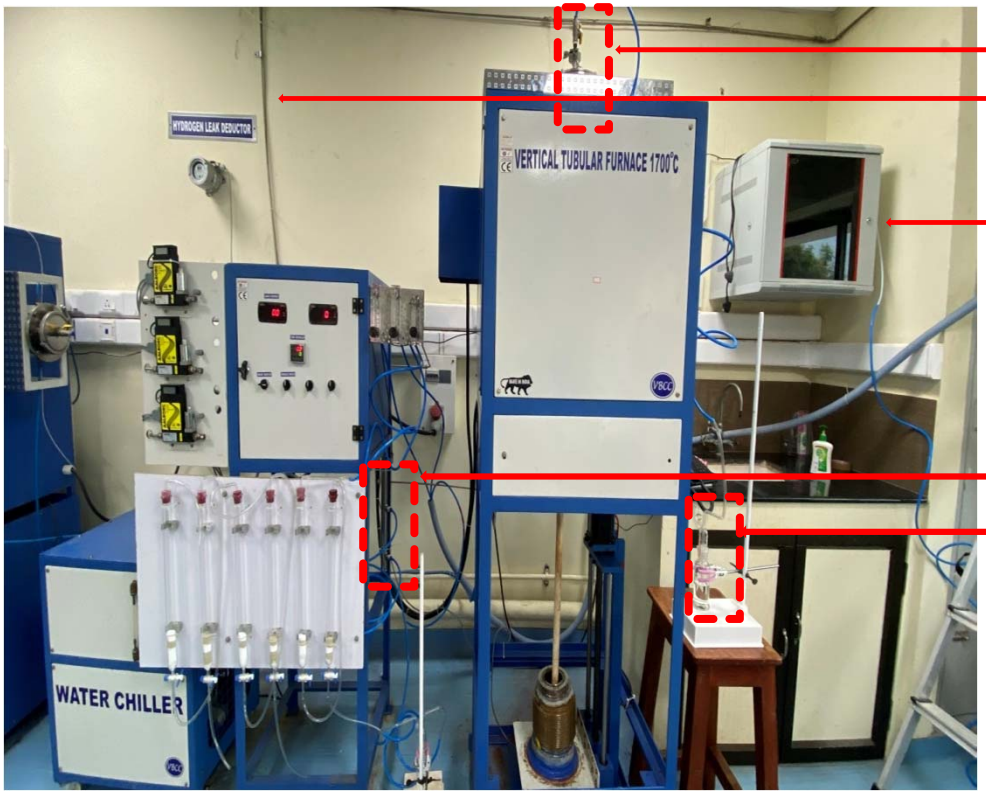


Cooling Arrangement

Maximum Power 6kW, 2.45GHz, Maximum Temp. 1700°C

Four Segment (Three heating cycle +one cooling cycle)
Operating Mode (Hybrid Mode , Only Resistance Heating, Only Microwave Heating)

Vertical Tubular Furnace Setup



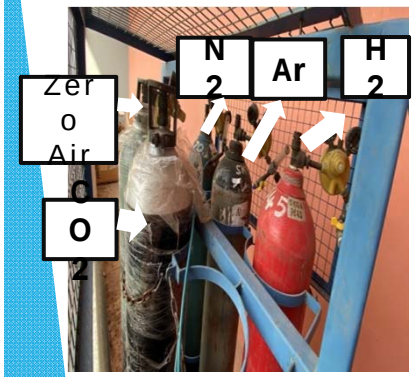
Gas Exit

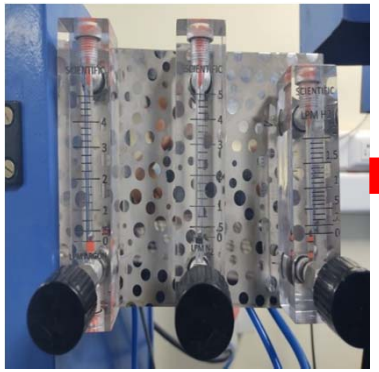
Hydrogen gas Inlet (SS Pipe)

Gas Analyzer

Gas Mixing Chamber (Outlet)

Gas Bubbling srtup (Gas Leakage) Check)





Gas Inlet Flow Meter (1-5LPM)

Gas Cleaning System

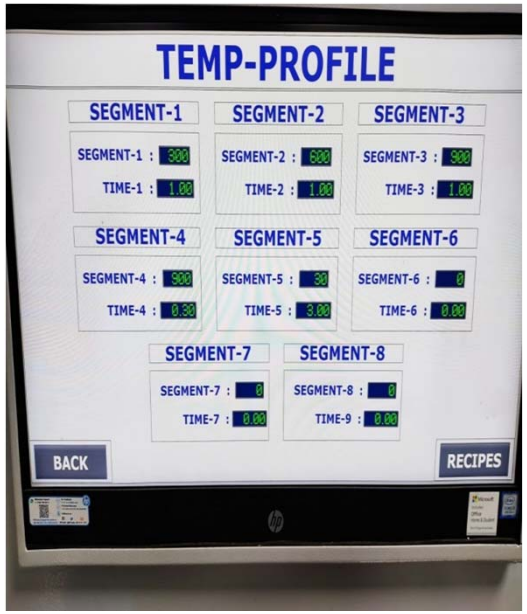
Water Cooling Inlet

Alumina Crucible

Load Cell

Gas Mixture Inlet

Vertical Tubular Furnace



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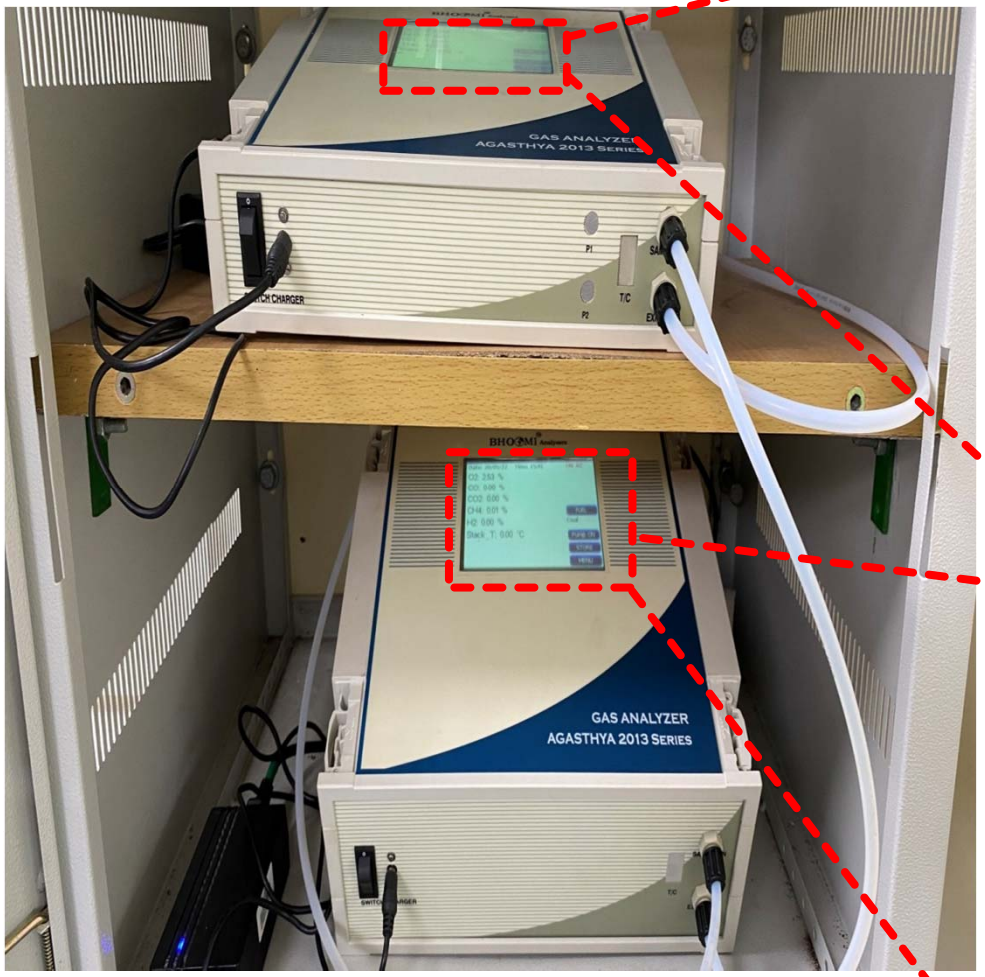
VERTICAL TUBULAR FURNACE

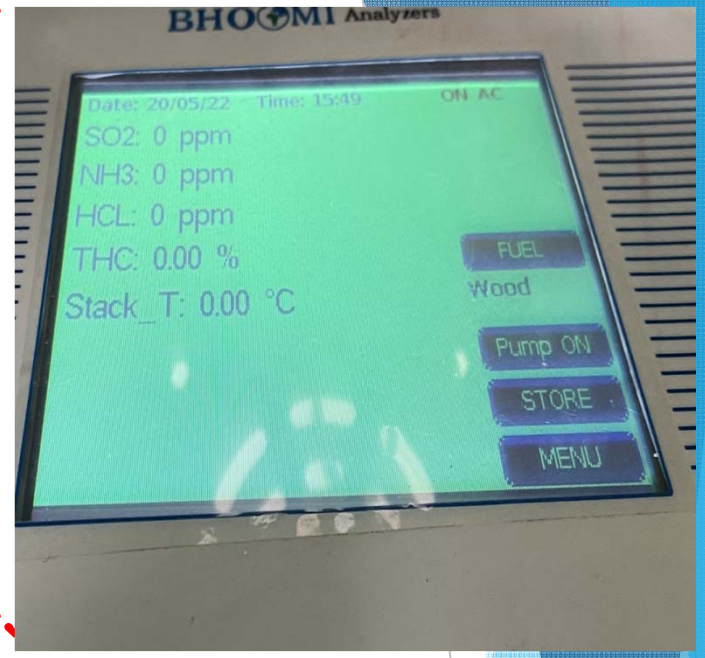
DATA-LOG

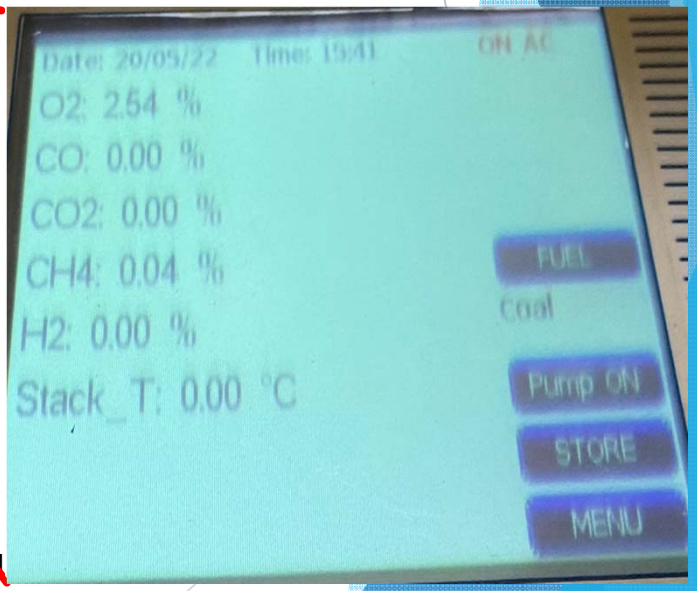
	A	B	C	D	E
1	DATE	TIME	TEMP-SV	TEMP-PV	LOAD in gm
2	4/28/2022	11:30:58 AM	0	166	61.90999985
3	4/28/2022	11:31:11 AM	207	202	61.90999985
4	4/28/2022	11:32:27 AM	212	202	61.90999985
5	4/28/2022	11:33:10 AM	218	204	61.86000061
6	4/28/2022	11:34:12 AM	222	209	61.81999969
7	4/28/2022	11:35:13 AM	227	215	61.81999969
8	4/28/2022	11:36:09 AM	237	228	61.77000046
9	4/28/2022	11:37:26 AM	243	235	61.72000122
10	4/28/2022	11:38:32 AM	247	241	61.66999817
11	4/28/2022	11:39:08 AM	252	247	61.66999817
12	4/28/2022	11:40:25 AM	257	253	61.66999817
13	4/28/2022	11:41:13 AM	262	259	61.56999969
14	4/28/2022	11:42:09 AM	267	264	61.56999969
15	4/28/2022	11:43:27 AM	272	270	61.52000046
16	4/28/2022	11:44:11 AM	278	276	61.52000046
17	4/28/2022	11:45:08 AM	282	281	61.47000122
18	4/28/2022	11:46:11 AM	287	286	61.47000122
19	4/28/2022	11:47:08 AM	293	291	61.41999817
20	4/28/2022	11:48:07 AM	297	296	61.36999893
21	4/28/2022	11:49:06 AM	302	301	61.33000183
22	4/28/2022	11:50:06 AM	307	306	61.33000183
23	4/28/2022	11:51:06 AM	312	311	61.27999878
24	4/28/2022	11:52:07 AM	317	317	61.22999954
25	4/28/2022	11:53:06 AM	322	322	61.22999954
26	4/28/2022	11:54:05 AM	327	327	61.18000031
27	4/28/2022	11:55:06 AM	332	332	61.13000107
28	4/28/2022	11:56:06 AM	337	337	61.13000107
29	4/28/2022	11:57:06 AM	342	342	61.08000183
30	4/28/2022	11:58:06 AM	347	347	61.08000183
31	4/28/2022	11:59:07 AM	352	352	60.97999954
32	4/28/2022	12:00:06 PM	357	357	60.97999954
33	4/28/2022	12:01:05 PM	362	362	60.93000031

Sheet1

Gas Analyzer

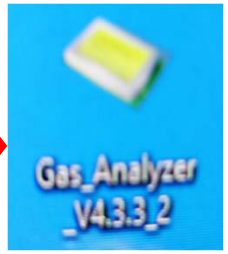




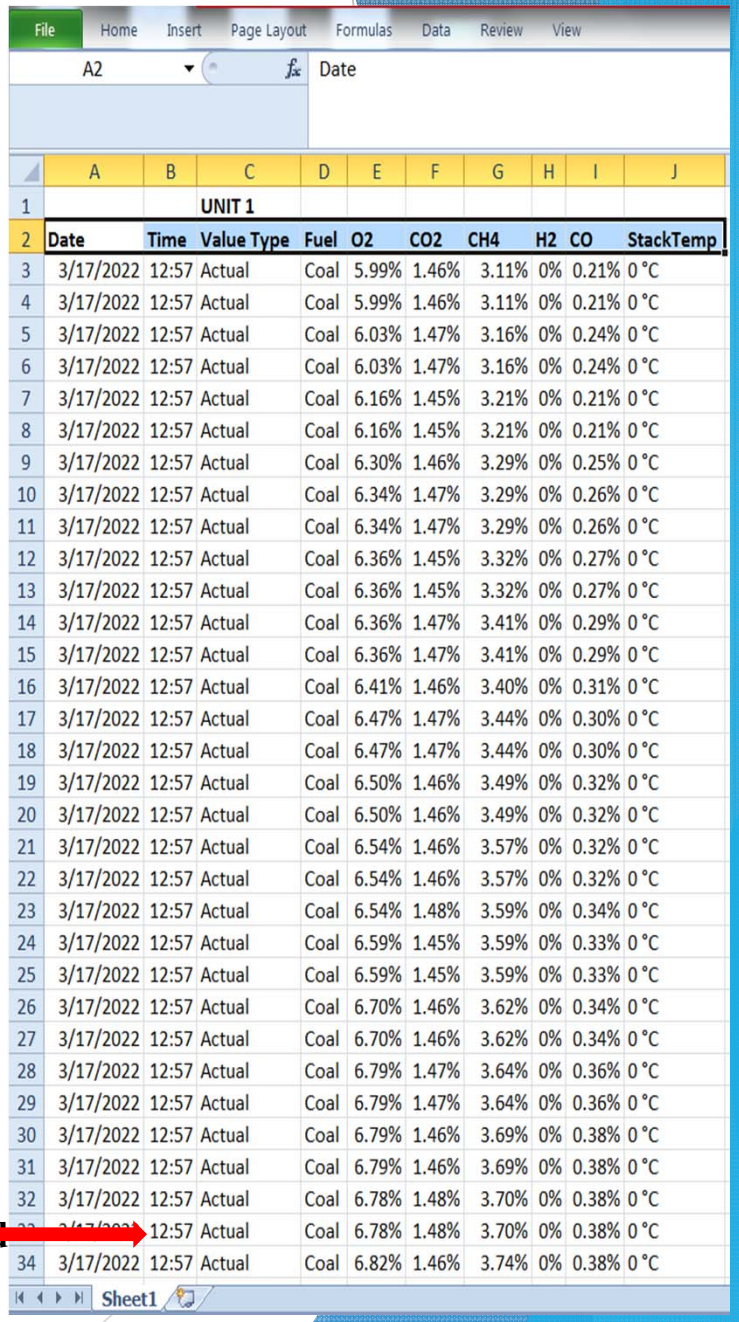


Model BI 7230
(agasthya 2013 series)
Operating Principle : Infrared gas analysis (IRGA)
Sensors Used: Advanced NDIR sensors and electrochemical

Gas Analyzer



Exit Gas Cleaning Unit Every Second Data Recorded



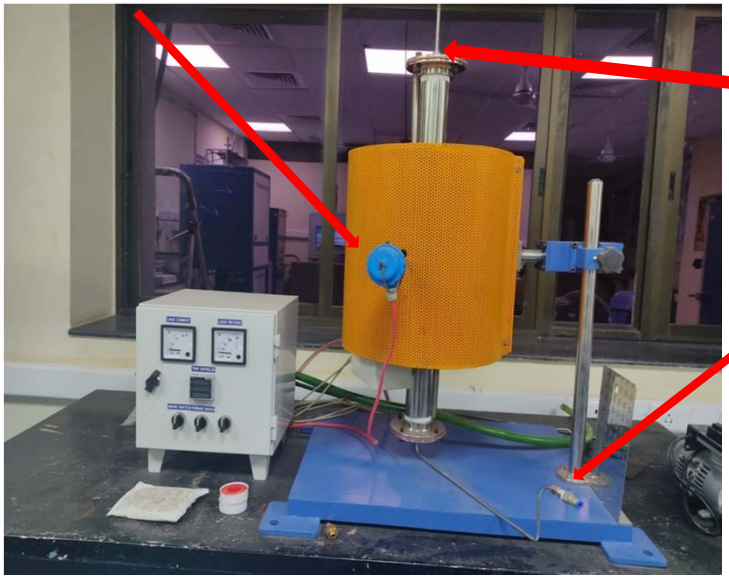
File | Home | Insert | Page Layout | Formulas | Data | Review | View

A2 | Date

	A	B	C	D	E	F	G	H	I	J
1			UNIT 1							
2	Date	Time	Value Type	Fuel	O2	CO2	CH4	H2	CO	StackTemp
3	3/17/2022	12:57	Actual	Coal	5.99%	1.46%	3.11%	0%	0.21%	0 °C
4	3/17/2022	12:57	Actual	Coal	5.99%	1.46%	3.11%	0%	0.21%	0 °C
5	3/17/2022	12:57	Actual	Coal	6.03%	1.47%	3.16%	0%	0.24%	0 °C
6	3/17/2022	12:57	Actual	Coal	6.03%	1.47%	3.16%	0%	0.24%	0 °C
7	3/17/2022	12:57	Actual	Coal	6.16%	1.45%	3.21%	0%	0.21%	0 °C
8	3/17/2022	12:57	Actual	Coal	6.16%	1.45%	3.21%	0%	0.21%	0 °C
9	3/17/2022	12:57	Actual	Coal	6.30%	1.46%	3.29%	0%	0.25%	0 °C
10	3/17/2022	12:57	Actual	Coal	6.34%	1.47%	3.29%	0%	0.26%	0 °C
11	3/17/2022	12:57	Actual	Coal	6.34%	1.47%	3.29%	0%	0.26%	0 °C
12	3/17/2022	12:57	Actual	Coal	6.36%	1.45%	3.32%	0%	0.27%	0 °C
13	3/17/2022	12:57	Actual	Coal	6.36%	1.45%	3.32%	0%	0.27%	0 °C
14	3/17/2022	12:57	Actual	Coal	6.36%	1.47%	3.41%	0%	0.29%	0 °C
15	3/17/2022	12:57	Actual	Coal	6.36%	1.47%	3.41%	0%	0.29%	0 °C
16	3/17/2022	12:57	Actual	Coal	6.41%	1.46%	3.40%	0%	0.31%	0 °C
17	3/17/2022	12:57	Actual	Coal	6.47%	1.47%	3.44%	0%	0.30%	0 °C
18	3/17/2022	12:57	Actual	Coal	6.47%	1.47%	3.44%	0%	0.30%	0 °C
19	3/17/2022	12:57	Actual	Coal	6.50%	1.46%	3.49%	0%	0.32%	0 °C
20	3/17/2022	12:57	Actual	Coal	6.50%	1.46%	3.49%	0%	0.32%	0 °C
21	3/17/2022	12:57	Actual	Coal	6.54%	1.46%	3.57%	0%	0.32%	0 °C
22	3/17/2022	12:57	Actual	Coal	6.54%	1.46%	3.57%	0%	0.32%	0 °C
23	3/17/2022	12:57	Actual	Coal	6.54%	1.48%	3.59%	0%	0.34%	0 °C
24	3/17/2022	12:57	Actual	Coal	6.59%	1.45%	3.59%	0%	0.33%	0 °C
25	3/17/2022	12:57	Actual	Coal	6.59%	1.45%	3.59%	0%	0.33%	0 °C
26	3/17/2022	12:57	Actual	Coal	6.70%	1.46%	3.62%	0%	0.34%	0 °C
27	3/17/2022	12:57	Actual	Coal	6.70%	1.46%	3.62%	0%	0.34%	0 °C
28	3/17/2022	12:57	Actual	Coal	6.79%	1.47%	3.64%	0%	0.36%	0 °C
29	3/17/2022	12:57	Actual	Coal	6.79%	1.47%	3.64%	0%	0.36%	0 °C
30	3/17/2022	12:57	Actual	Coal	6.79%	1.46%	3.69%	0%	0.38%	0 °C
31	3/17/2022	12:57	Actual	Coal	6.79%	1.46%	3.69%	0%	0.38%	0 °C
32	3/17/2022	12:57	Actual	Coal	6.78%	1.48%	3.70%	0%	0.38%	0 °C
		12:57	Actual	Coal	6.78%	1.48%	3.70%	0%	0.38%	0 °C
34	3/17/2022	12:57	Actual	Coal	6.82%	1.46%	3.74%	0%	0.38%	0 °C

Sheet1

CO Generator tubular furnace



CO Outlet

CO2 Inlet

20 Tons Cold pressing machi

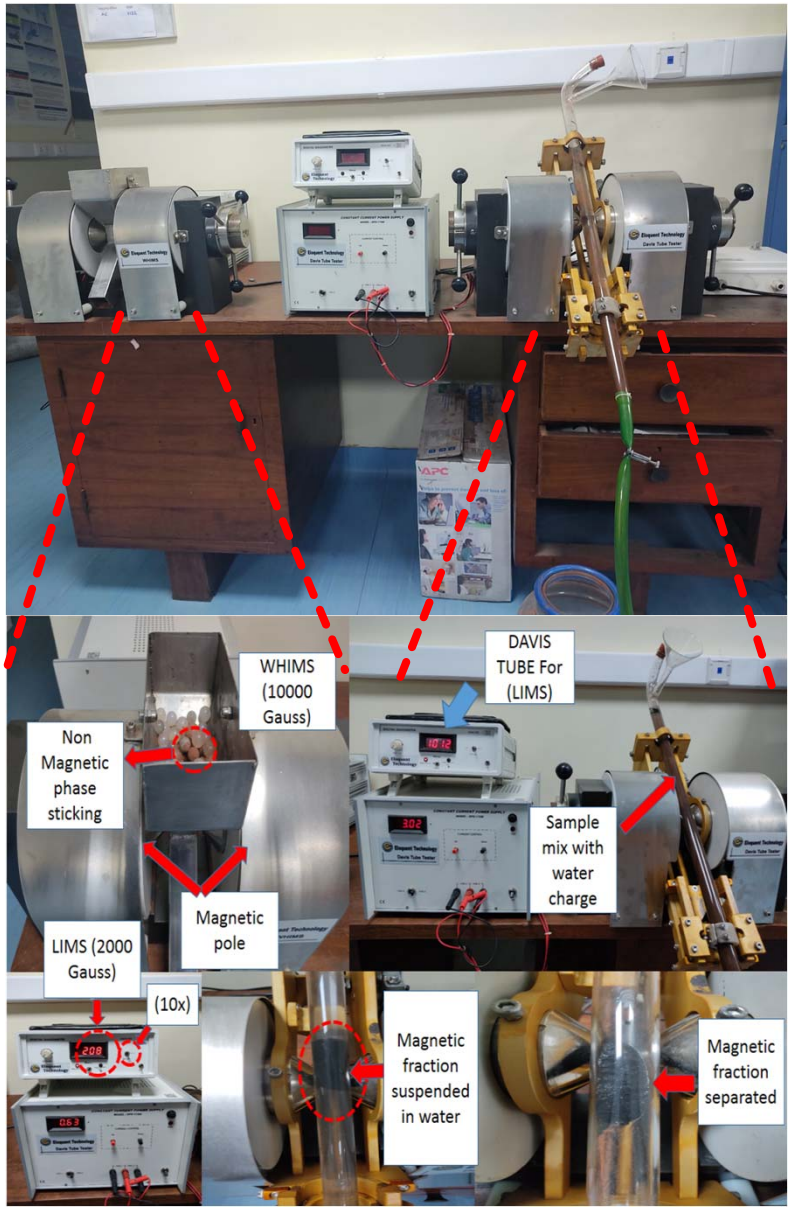
5 Kg jar mill

Sieve analyzer

RPM Controller

Time Controller

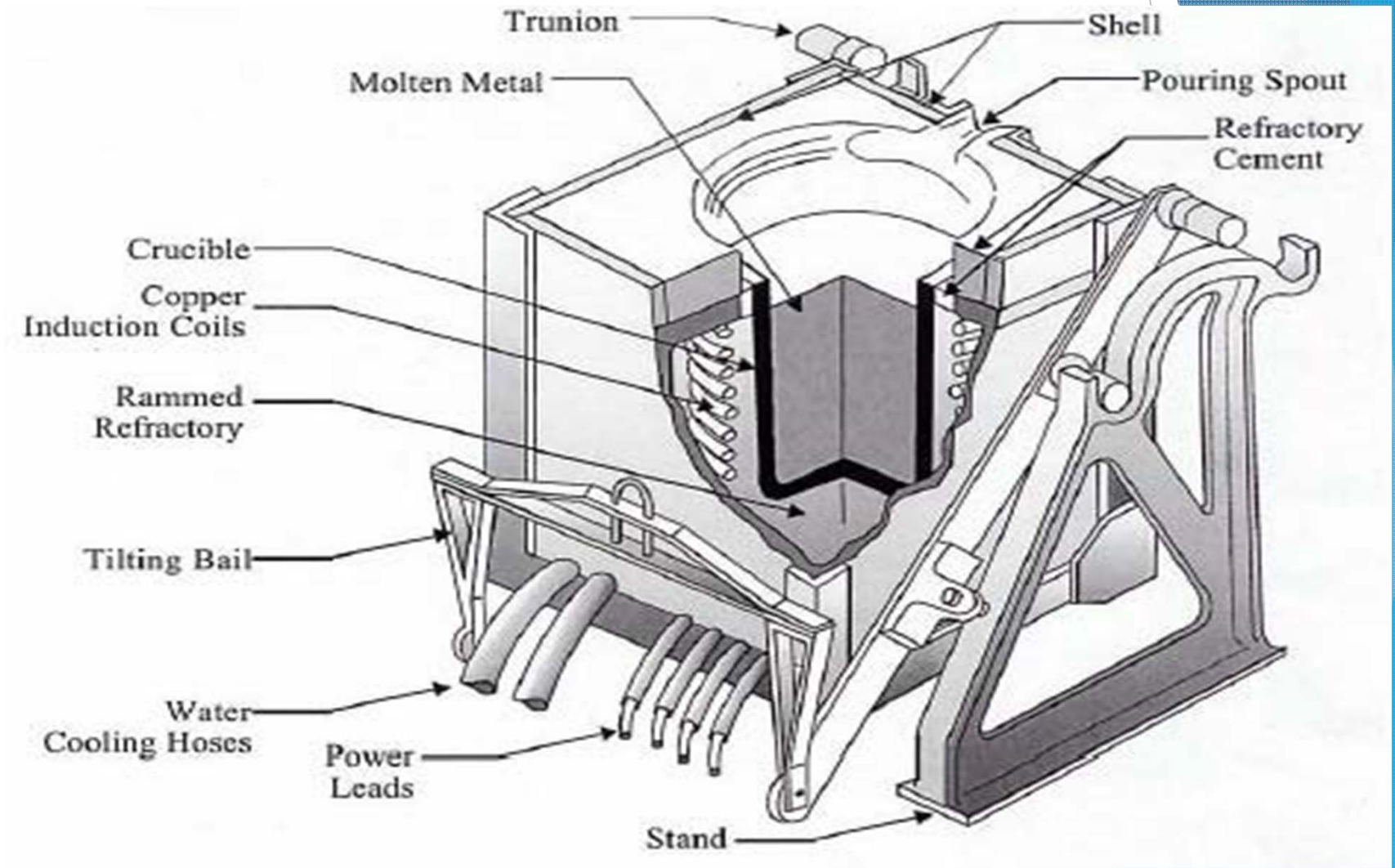
Magnetic Separation Unit



Horizontal Tubular Furnace

Vacuum Pump (10^(-3) bar)

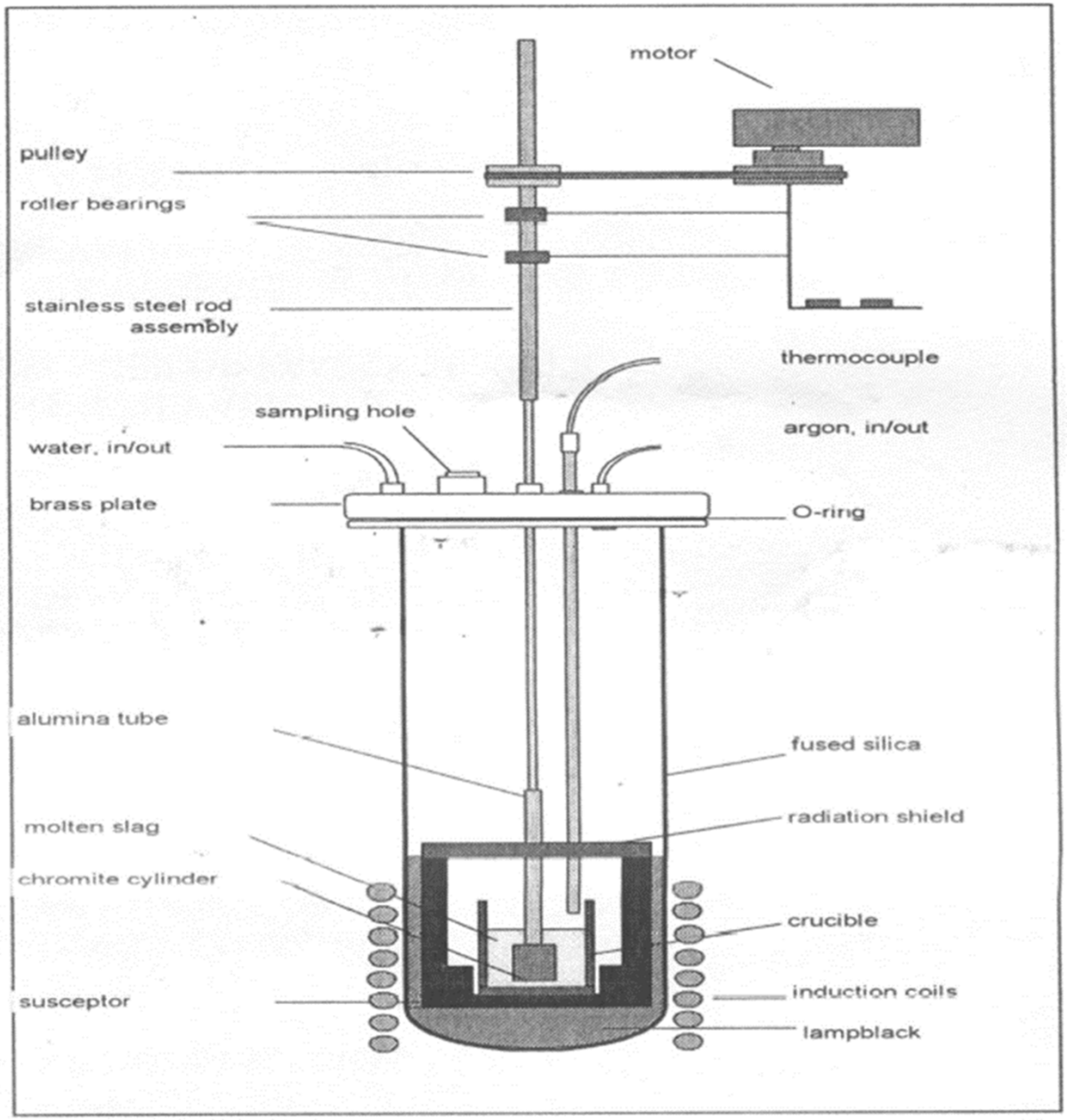
Induction tilt furnace for melting of steel and slag—under process



Video available at the following Youtube link:

https://www.youtube.com/@centerforpyrometallurgy-ii1768

Induction Rotating Cylinder Furnace along with Motor, Gear Box—under process



Video available at the following Youtube link:

https://www.youtube.com/@centerforpyrometallurgy-iit1768


HYDROGEN LEAK DEDUCTOR
HORIZONTAL TUBULAR FURNACE 1700°C
KIMTECH

THANK YOU