सेल SAIL
भिलाई इस्पात संयंत्र
BHILAI STEEL PLANT

A REPORT ON

"DATA DRIVEN ANALYSIS AND OPTIMIZATION OF FUEL RATE USING BLAST FURNACE PARAMETERS"

PIYUSH NARAYAN RAI (P25/S107)

BACHELOR OF TECHNOLOGY
METALLURGICAL AND MATERIALS ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY DURGAPUR
DURGAPUR
उद्योगः पुरुषस्य लक्षणम्

NATIONAL INSTITUTE OF TECHNOLOGY DURGAPUR

CERTIFICATE

This is to certify that Bhavesh Kalihari, Piyush Narayan Rai, Amit Saggam and Pragati Mishra has worked under my guidance for completion of their project on "DATA DRIVEN ANALYSIS AND OPTIMIZATION OF FUEL RATE USING BLAST FURNACE PARAMETERS " in Blast furnace division, Bhilai Steel Plant (BSP) from 05 May 2024 to 31st May 2024. Apart from suggestions made by me, the credit for all experimental work goes to them. I appreciate their hard working, involvement and tenacity to complete their project well in time.

Shri. H.K. Verma

Shri. Satyabrata Sutar

General Manager	Assistant General Manager
SAIL, Bhilai Steel Plant	SAIL, Bhilai Steel Plant

ACKNOWLEDGEMENT

We would like to express our sincere gratitude and appreciation to all those who have contributed us to the completion of this project.

First and foremost, we are deeply thankful to Shri. Satyabrata Sutar for their guidance, support, and invaluable insights throughout this endeavour. Their expertise and dedication have been instrumental in shaping the direction of our work and enhancing its quality. Their valuable feedback and constructive criticism, have immensely contributed to the refinement of this project.

We wish to thank and acknowledge all the help rendered by Shri. H K Verma . He encouraged us at difficult moment of study and instilled a lot of confidence.

Additionally, we would like to thank our team member of this project i.e. B Shashank Kumar, Chitesh Turkar and Krishna Kumar.Their insights, discussions, and motivation have been invaluable in shaping our ideas and maintaining our team enthusiasm.

Last but certainly not least, we want to acknowledge our family for their unwavering love, encouragement and understanding. Their constant support and belief in ourselves have been the driving force behind our achievements.

Thank you all for your invaluable support, guidance and encouragement.

ABSTRACT

Bhilai Steel Plant is the flagship of SAIL. The production capacity of Hot Metal, Crude Steel & Saleable Steel after completion of Modernisation & Expansion Programme (MEP Plant/unit wise) is as under:

Hot Metal – 7.5 MT (Million Tonnes)

Crude Steel – 7 MT

Saleable Steel – 6.56 MT

BSP being an integrated steel plant, where the role of Blast furnace is very important & performance of Blast furnace is judged by two very important factors, its coke rate and productivity.

This project report presents a comprehensive, data-driven analysis of key operational parameters influencing fuel rate optimization in Blast Furnace 8 at SAIL Bhilai Steel Plant (BSP).

The report begins with an overview of the Bhilai Steel Plant and its major departments, followed by a detailed examination of vital blast furnace parameters, including hot blast temperature, moisture content, CO utilization efficiency, slag rate, flame temperature, and top pressure. The interrelation among these parameters is also analyzed to understand their collective influence on furnace performance.

Using real-time industrial data from Blast Furnace 8, a variety of machine learning models were developed and evaluated to predict fuel rate. Tools and technologies such as Python, Pandas and Scikit-learn were employed for data preprocessing, model training, and result visualization. After comparing multiple models, the best-performing model was selected based on accuracy and robustness.

The latter sections of the report delve into the interpretation of code, visual output plots, and a parameter-wise analysis of how each variable affects fuel rate. Finally, the report concludes with a summary of findings and practical recommendations for optimizing fuel consumption in blast furnace operations, potentially leading to improved energy efficiency and reduced operational costs.

CONTENTS

OVERVIEW

The Bhilai Steel Plant (BSP), located in Bhilai, in the Indian state of Chhattisgarh, is India's First and main producer of steel rails, as well as a major producer of wide steel plates and othersteel products.

Eleven times winner of Prime Minister's Trophy for Best Integrated Steel Plant in the Country,Bhilai Steel Plant (BSP) has been India's sole producer and supplier of world class Rails for Indian Railways including 260 metre long rails, and a major proudcer of large variety of wideand heavy steel plates and structural steel. With an annual production capacity of 5 MT of saleable steel, the plant also specializes in other products such as wire rods and merchant products. The entire range of TMT products (Bars and Rods) produced by the plant is of earthquake resistant grade and superior quality. The plant also produces heavy structural including channels and beans.

Bhilai Steel Plant functions as a unit of SAIL, with corporate offices in New Delhi. The chief Executive officer controls operations of the plant, township and iron mines. The CEO is assisted by his D.R.O.s(Direct Reporting Officers), i.e. the functional heads, Executive Directors, general Manager concept of zonal heads, and HODs who integrate functions with Clear accountability for achieving corporate vision, company goals and objectives.

Since BSP is accredited with ISO 9001:2000 Quality Management System Standard, all salteable products of Plant come under the ISO umbrella. The Plant's HR Dept. is also Certifiedwith ISO 9001:2000 QMS Standard. ISO: 141001 has been awarded for environment Management System in the Plant, Township and Dalli Mines. The Plant is accredited with SA:8000 certification for social accountability and the OHSAS-18001 Certification for Occupational Health and Safety.

BSP has receive Integrated Management System (IMS) Certificate by a single certifiying agency (M/s DNV), Integrating QMS, EMS, and OHSAS & SAMS- becoming the first SAIL unit and among few corporate houses in India to achieve this unique distinction.

Since BSP is accredited with ISO 9001:2000 Quality Management System Standard, all saleable products of Plant come under the ISO umbrella. The Plant's HR Dept. is also Certifiedwith ISO 9001:2000 QMS Standard. ISO: 141001 has been awarded for environment Management System in the Plant, Township and

Dalli Mines. The Plant is accredited with SA:8000 certification for social accountability and the OHSAS-18001 Certification for Occupational Health and Safety.

BSP has receive Integrated Management System (IMS) Certificate by a single certifiying agency (M/s DNV), Integrating QMS, EMS, and OHSAS & SAMS- becoming the first SAIL unit and among few corporate houses in India to achieve this unique distinction.

Sources of Raw materials in BSP –
Presently, the total requirement of iron ore of Bhilai Steel Plant is met from Dalli Rajhara IronOre Complex (IOC). In view of IOC's rapidly depleting reserves, BSP is opening an iron ore mine at Rowghat, about 80 kilometres (50 mi) from Dalli Rajhara in Narayanpur District of Chhattisgarh. Accordingly, Bhilai Steel Plant will develop the mine in Block-A of deposit-F of Rowghat with a production capacity of 14.0 MT per year during 2011-12.

S.No.	Raw materials	Sources
1	Iron Ore Fines	Dalli Rajhra
2	Iron ore lumps	Dalli Rajhra
3	High Silica Limestone	Nandini
4	High Silica Dolomite	Hirri Mines
5	Low Silica Limestone	Jaiselmer, katni, kuteshwar
6	High Silica Mn Ore	Rantake Tirodi
7	Coal (Indegenous)	Bhojudh, Nandan,Rajarappa
8	Coal (Imported)	Australia, New Zealand

Departments in Bhilai Steel Plant

- Rail & Structural Mill
- Coke Ovens
- Blast Furnace
- Steel Melting Shops
- Mills
- Sinter Plant
- Research & Control Lab
- Foundry
- Rail & Structural Mill

BLAST FURNACE PARAMETERS

In blast furnace ironmaking, fuel rate (typically the coke and injectant consumption per ton of hot metal) is a key performance indicator. Fuel costs often comprise 40–60% of hot metal production costs, so minimizing the fuel rate is essential for economic and environmental reasons. The fuel rate is influenced by many operational parameters, including the blast air temperature, burden moisture, gas utilization, slag volume, flame (raceway) temperature, and furnace top pressure. Each of these parameters affects the furnace's thermal balance and reduction efficiency, and thus the required fuel input. Below we examine the role of each parameter, its effect on fuel consumption, and how it interrelates with overall furnace performance.

- Hot Blast Temperature

Pre-heated air, or 'hot blast' is blown into the blast furnace via the tuyeres at a temperature of up to 1200°C. The hot blast burns the fuel that is in front of the tuyere, which is either coke or another fuel that has been injected into the furnace through the tuyeres. This burning generates a very hot flame and at the same time the oxygen in the blast is transformed into gaseous carbon monoxide (CO). The resulting gas has a flame temperature of between 2000 and 2300°C. Since the gas flow is very high, the residence time of the gas is very short, typically 6-10 seconds. In the 6-10 seconds, the heat generated at the tuyeres is transferred to the burden: the gas leaves the furnace with an average temperature of 100-150°C. However, in the centre of the furnace the coke chimney will allow much higher temperatures to be observed, up to 600 880°C or even higher. In the same 6-10 seconds the gas carries out a number of chemical reactions that go along way to make the furnace such an efficient process for the production of iron. Hot blast temperature is normally at or close to its maximum. The cheapest fuel used in the BF is the BF gas itself and this reduces the coke rate requirement.

Raising the blast air temperature reduces the coke required to reach the same internal temperatures. Studies report that when maintaining hot blast between about 1000 °C and 1200 °C, each 100 °C increase cuts the coke rate by roughly 2.8%. In practice, higher stove or stove bank performance (raising blast above nominal levels) has been shown to save significant fuel, on the order of 80–85 MJ per ton of hot metal. Optimizing blast temperature is thus crucial: too low a temperature forces extra coke firing, while too high a temperature can overheat equipment and risk damage. In summary, maintaining an elevated, stable hot blast temperature maximizes heat transfer to the burden and lowers the fuel rate.

- Moisture injection

The majority of the moisture that is introduced to the blast furnace with the raw materials is in the fines. By limiting the fines, the moisture is also reduced. However, in some cases the raw materials themselves carry a lot of inherent moisture. This is often the case with pellets that are stored outdoors, where they are subject to wet weather conditions. The installation of drying facilities is very expensive and difficult to maintain, and so usually the wet materials are charged directly to the blast furnace.

However fluctuations in the moisture levels can lead to changes in the thermal level of the furnace, as the additional moisture that is present in the coke and the pellets will not be accounted for in the weighing system as moisture, so there will be inaccuracies in the real coke rate that is being charged. Where moisture is added in place of coke the furnace cools and so the normal thermal control procedures will be activated, usually calling for additional fuel. If the moisture level reduces again, the furnace will warm up. If this is allowed to continue, the furnace will enter a thermal cycle that will in turn consume more fuel than required, and be at risk of chilling. When batch of pellets are charged to the furnace the top temperature will decrease with the additional moisture, but the furnace will start to warm up due to the lower amount of iron that is being charged to the furnace.

Coke rate changes will normally be made to correct for this warm up, however once this batch of wet pellets have been consumed it is very important to realize that the furnace will then cool down due to the additional iron that is being charged. If this is not anticipated then the furnace can cool down very quickly.

so it is better to anticipate this change by increasing coke rate when it is known that the wet pellets have been consumed and dry pellets are soon to arrive. Ideally, coke and pellet moisture gauges can be installed to monitor and correct for any changes on-line. These moisture gauges take regular readings of the as-charged moisture levels for coke and pellets and will make corrections for the weight, so that the required quantity of the material is charged.

- Carbon Monoxide (CO) Utilization Efficiency / Gas utilization Efficiency

Firstly, the heat with a temperature in excess of 1400°C is heating up the coke and the melting materials flowing over the coke. In the temperature range from 1200-1350°C the burden will soften and stick together rather than melt. In the cohesive zone the remaining oxygen in the ore burden is removed, which generates additional carbon monoxide gas. This is referred to as the direct reduction reaction or solution loss. At the high local temperature, the remaining oxygen of the melting burden reacts with coke and generates extra carbon monoxide gas. In general, the ore burden which is charged into the furnace has close to 3 atoms of oxygen for every 2 atoms of iron. About 2 of the 3 oxygen atoms are removed by reaction with gas and about 1 of the 3 oxygen atoms is removed by this direct reduction reaction Since the direct reduction reaction needs a lot of energy, the efficiency of the furnace is largely dependent on the amount of oxygen removed from the burden materials before reaching the 1200°C critical temperature. When the gas is cooling down further, below 1200°C, the gas contains a high amount of carbon monoxide and hydrogen. These components are effective in removing oxygen from the iron units and they form carbon dioxide and water, which leave the furnace out from the top. This is called 'gas reduction'. The oxygen content of the ore burden is reduced with gas. As soon as the gas emperature is below 500°C, the chemical reactions stop and the gas uses only its heat for heating up the burden and expelling moisture from the burden and coke.

➢ ETA CO / Gas Utilization Efficiency

ETA CO / Gas Utilization Efficiency = (CO_2 / (CO + CO_2)) × 100

- $3Fe_2O_3$ + CO- $2Fe_3O_4$ + CO_2
  Hematite + Carbon Monoxide- Magnetite + Carbon Dioxide
- Fe_3O_4 + CO- 3FeO +CO_2
  Magnetite + Carbon Monoxide- Wustite + Carbon Dioxide
- FeO + CO- Fe +CO_2
  Wustite + Carbon Monoxide- Iron metal (solid) + Carbon Dioxide

CO utilization efficiency in blast furnace top gas, shows how well CO is used for ore reduction. A **low ratio** means more CO is converted to CO_2, indicating efficient fuel use. A **high ratio** signals wasted CO and higher coke demand. Improving CO efficiency—through better gas-solid contact or longer gas residence time—lowers coke consumption. Furnace controls monitor this ratio to optimize fuel use, adjusting factors like oxygen enrichment and coke injection to ensure CO is effectively consumed.

➢ Slag Rate

The blast furnace process results in liquid iron and slag being produced. These two liquids drip down into the coke-filled hearth of the blast furnace where they wait to be tapped, or cast from the furnace. The densities of the two liquids are quite different; with iron (7.2 t/m3) being three times that of slag (2.4 t/m3). This difference leads to very good separation between the iron and the slag once it is outside the furnace. If the slag level is so high that it reaches the tuyeres then the gas flow will be severely affected. This can result in poor reduction of the burden and therefore a chilling furnace. The slag can be blown high up in the dead man coke, impeding normal gas distribution.

A higher slag rate increases fuel consumption because more flux and impurities must be melted, requiring additional heat. This raises the furnace's endothermic thm and coke use. While slag is necessary to capture impurities, minimizing excess slag improves fuel efficiency by reducing heat losses. Optimal slag rates balance impurity removal with lower thermal and fuel demands.

- Flame Temperature

The flame temperature in the raceway is the temperature that the raceway gas reaches as soon as all oxygen and water have been converted to CO and H2. The flame temperature is a theoretical concept, since not all reactions are completed in the raceway. From a theoretical point of view, it should be calculated from a heat balance calculation over the raceway. For practical purposes linear formulas have been derived, basically all steel plants use their own formula, but the standard calculation as defined by AISI is

Metric Units

RAFT = 1489 + 0.82xBT – 5.705xBM + 52.778x(OE) – 18.1xCoal/WCx100 – 43.01xOil/WCx100 – 27.9xTar/WCx100 – 50.66xNG/WCx100

Where:		
	BT	= Blast Temperature in °C
	BM	= Blast Moisture in grams/Nm^3 dry blast
	OE	= Oxygen enrichment, %02 – 21%
	Oil	= Dry oil injection rate in kg/tHM
	Tar	= Dry tar injection rate in kg/tHM
	Coal	= Dry coal injection rate in kg/tHM
	NG	= Natural gas injection rate in kg/tHM
	WC	= Wind Consumption m^3/tHM

Flame temperatures are normally in the range of 2000-2300°C. The flame temperature is influenced by the raceway conditions. Qualitatively: the flame temperature increases, if: Hot blast temperature increases, Oxygen percentage in blast increases. The flame temperature decreases, if: Moisture increases in the blast, Fuel injection rate increases, since cold fuels are burned instead of hot coke. The precise effect depends also on auxiliary fuel composition. Some companies tend to keep flame temperature constant. In itself this is a good strategy, since a blast furnace runs best if you keep everything constant. However, we have experienced that furnaces can operate well in a wide range of flame temperatures.

Higher flame temperatures improve combustion efficiency by converting more fuel energy into heat, reducing coke use. Methods like oxygen enrichment and hot blast increase this temperature, enhancing heat transfer to the burden. However, too low a flame temperature causes incomplete combustion, while too high can damage furnace materials. Optimizing flame temperature boosts thermal efficiency and lowers the fuel rate.

- Top Pressure

For the BF operator, one of the main raw material concerns is that of the fines thming. This is the proportion of undersize material that is in the furnace. The direct effect of a high fines thming is that it will affect the permeability of the furnace. Whether it is ferrous or carbon fines, the result is that the gaps through which the gasses pass will be blocked. The first effect of this is that the blast pressure will increase, increasing the difference between the top pressure and the blast pressure, known as delta-P. As the top pressure is usually kept constant, in the case where the blast pressure is limited by the structural integrity of the stoves, the wind rate must be reduced whenever the blast pressure increases.
The delta-P, ΔP, or pressure differential is a number calculated by subtracting the top pressure from the blast pressure.

That is ΔP = Blast Pressure - Top Pressure.

As the blast pressure increases it will increase the upward force on the descending burden, causing it to 'hang'. If nothing is done to relieve the pressure, then the gas will find an escape route, often against the wall, resulting in high heat losses, or through the burden, known as channeling. The sudden pressure relief then allows the burden to descend in an uncontrolled way, known as a 'slip'. There are of course other causes if the delta-P increasing, and for hanging and slipping to occur, but an increase in fines thming, without any actions taken to compensate for it, is likely to cause problems with the furnace operation.

Blast furnace top pressure (gauge pressure at the furnace throat) influences gas flow and retention time. Typically, it's slightly negative or low positive; increasing it (e.g., above 0.5 bar) improves gas-solid reactions. Higher pressure slows gas up flow, increasing contact time between reducing gases and descending ore, which enhances reduction and reduces coke usage. This results in lower fuel rates and more efficient operation. Higher pressure also stabilizes furnace performance and can enable power generation from off-gases, offsetting plant energy needs. Optimizing top pressure reduces coke and injectant requirements while improving heat utilization.

BLAST FURNACE #8 DATA

Blast Furnace Basic Data

S.No	Parameter	Unit	Value
1	No. of Blast Furnace	-	1
2	Useful Volume of BF	m^3	4060
3	Working Volume of BF	m^3	3445
4	Hearth Diameter (approx.)	mm	13400
5	No. of Cast House	Nos.	2
6	Nos. of Taphole in Each Cast House	Nos.	2
7	Angle Between Taphole	DEG.	72°
8	No. of Tuyeres	Nos.	36
9	Production per Day	TPD	8030 (AVG), 8400 (MAX)
10	Ash Content of Coke	%	≤ 15 (MAX)
11	Ash of Coal	%	9–10
12	Sinter in Burden	%	~67
13	Sized Ore in Burden	%	~12
14	Pellet in Burden	%	~11
15	Availability of Blast Furnace	DAY/YEAR	350 (MIN)

Input Materials Consumption

Parameter	Unit	Value
Iron Ore Lump	kg/thm	358
Sinter/Pellet	kg/thm	1082 / 178
Lime Stone, Quartzite	-	As per requirement
Coke Rate (Including 20 kg/thm Nut Coke)	kg/thm	396 (MAX)
Coal Dust (CDI Coal)	kg/thm	150 (AVG), 200 (Design)

Blast Characteristics

Parameter	Unit	Value
Volume (Dry Basis)	Nm^3/thm	1009
Temperature	°C	1250 (MAX)
Humidity	gm/Nm^3	45
Oxygen Enrichment	%	6

Top Gas Characteristics

Parameter	Unit	Value
Pressure (Max. Operating)	kg/cm^2	2.5
Volume	Nm^3/thm	1566
Temperature (AVG)	°C	261
CO	%	24.3
CO_2	%	20.4
N_2	%	46.5
O_2	%	0.5

CO/N_2	-	0.52
Calorific Value	$Kcal/Nm^3$	875

Hot Metal Characteristics

Parameter	Unit	Value
Si	%	0.5-0.6
S / P	%	0.035 / 0.13
Desired Hot Metal Temp.	°C	1500

Slag Characteristics

Parameter	Unit	Value
Al_2O_3	%	19.14
MgO	%	8
Basicity	-	0.95
Slag Rate	kg/thm	295
Slag Temperature	°C	1550

Geometrical Features

Parameter	Unit	Value
Hearth Diameter	mm	13400
Belly Diameter	mm	15170
Throat Diameter	mm	9900
Nos. of Tuyere	Nos.	36
Nos. of Taphole	Nos.	4
Taphole Inclination	°	10.2°
Shaft Angle	°	81°24’
Bosh Angle	°	77°22’77”
Hearth Sump Depth	mm	2750
Distance Tuyere/Taphole	mm	4450
Distance Centre Tuyere/Top Hearth	mm	8000
Bosh Height	mm	3950
Belly Height	mm	1320
Stack Height	mm	17450
Working Height	mm	25900
Useful Height	mm	21550
Throat Height	mm	4350
Total Height (Hearth Bottom to Stock Level)	mm	33100
Height of Top of Copper Stave from Tuyere Centre Line	m	12.6 (MIN)
Percentage of Copper Stave Height w.r.t. Stack Height	%	33.0% (MIN)
Sump Depth Over Hearth Diameter	%	20.52%
Working Volume	m^3	3445
Inner Volume	m^3	4060

Cleaned Data of Blast Furnace 8 of SAIL BSP (01/04/2024 to 30/03/2025)

fuel rate	Steam Injection	ETA CO / CO efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
596.2	4.9	50.86	1094	452	2127.8	2.31
559.7	3	47.57	1097	454	2197.8	2.33
588	5.8	48.82	1096	474	2108.8	2.32
573.4	12.7	45.4	1099	466	2168.3	2.17
586.4	7.6	46.56	1083	472	2099.1	2.25
572.5	6.9	47.11	1076	475	2121.2	2.36
577.3	7.6	45.71	1078	464	2128.8	2.33
570.5	8.5	46.18	1098	450	2163.1	2.31
561.9	6.4	46.01	1097	455	2130.5	2.33
563.9	6.5	45.35	1087	468	2179	2.26
565.6	0.4	46.01	1089	478	2195	2.32
569.2	5.4	47.32	1090	475	2171.8	2.1
644	8.2	36.76	1091	490	2054.3	2.31
570.3	24.4	45.53	1102	455	1985.9	2.27
565.7	7.7	47.1	1131	465	2142.7	2.31
568.2	8.2	46.25	1138	448	2144.1	2.17
573	4	46.2	1140	453	2195.3	2.24
569.4	9.9	47.95	1137	466	2175.3	2.23
568.6	10	47.1	1136	461	2168.9	2.27
568.3	5	47.67	1123	487	2149.9	2.3
569.8	5.2	46.44	1101	492	2083.9	2.3
583.2	8.6	46.38	1114	508	2081.3	2.24
567	3.2	46.36	1124	523	2171.1	2.24
590.2	9.7	46.36	1118	513	2132.2	2.31
565.5	11.7	46.89	1124	501	2145.2	2.37
583.7	13.6	46.73	1131	510	2101.3	2.28
572.4	10.7	46.95	1137	502	2149.8	2.16
570	12.5	46.6	1145	507	2070.7	2.26
564.4	8	45.92	1153	509	2141.3	2.33
570.8	4.9	44.05	1173	515	2236	2.33
568.6	6.8	44.97	1180	538	2188.8	2.26
578.8	11	44.15	1183	576	2186.2	2.39
560.6	12	44.63	1186	520	2181.5	2.34
568.6	9	44.26	1181	518	2249.6	2.3
566.6	9.1	43.72	1178	509	2176.5	2.36
561.4	1.9	45.2	1179	531	2236.9	2.25
556.3	10.1	45.89	1177	547	2170.5	2.34
555.9	6.1	45.8	1176	503	2219.9	2.27
559.3	10	44.29	1179	515	2190.7	2.25
560	8	43.36	1180	529	2258.5	2.46
559.6	12.8	44.81	1176	494	2232.6	2.33

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
548.4	4.9	43.51	1178	517	2286.6	2.36
544.8	8.4	45.2	1178	493	2220.2	2.38
548	14	45.36	1165	483	2233.9	2.17
559.1	5	44.1	1158	512	2242	2.26
580.6	9.7	43.1	1177	525	2258.5	2.35
580.9	10	41.06	1178	559	2210.7	2.32
578.4	12	41.57	1180	506	2264.1	2.14
572.9	13.8	42.23	1177	530	2213.7	2.32
581.5	8	43.52	1175	527	2308.4	2.37
578.9	5	43.45	1177	515	2325.4	2.34
567.7	12	45.29	1176	492	2201.9	2.29
574.4	9.1	44.67	1176	483	2181.6	2.37
571.5	11	45.04	1178	509	2155	2.33
572.8	3.4	44.62	1177	567	2272.1	2.29
582.7	15.2	44.83	1179	546	2109.6	2.37
595	10	44.21	1179	526	2208.4	2.4
592.5	7.9	45.29	1178	505	2226.1	2.45
579.9	8	45.76	1178	481	2226.5	2.32
576.8	5.9	45.92	1178	529	2281.3	2.41
588.4	9.4	44.9	1177	502	2239.8	2.39
578.6	6.3	45.02	1176	506	2216.8	2.32
585.6	3	45.33	1176	525	2335.2	2.29
566.1	9	46.3	1175	498	2205.5	2.31
574.7	9	46.43	1175	528	2186.7	2.27
576.1	3	45.05	1178	528	2256.4	2.36
575.9	8.7	46.95	1176	500	2273.7	2.37
564.4	9.9	46.08	1160	553	2240.6	2.29
576.6	4	45.25	1170	514	2248.2	2.33
566.9	8.1	44.72	1178.05	530	2212.4	2.36
560.1	3	46.12	1177.92	518	2272.8	2.39
560.9	6	47.25	1176.08	506	2299.4	2.37
560.5	7.6	47.19	1177.38	516	2222.3	2.31
574.3	3.3	46	1176.33	518	2319.4	2.36
573.6	3.9	44.97	1178.96	517	2279.4	2.31
586.6	6.9	43.28	1181.21	546	2219.4	2.27
606.8	1.9	48.42	1180.83	531	2324.4	2.45
567.2	4.3	45.24	1182.75	528	2278.5	2.42
570.4	2.8	45.81	1183.46	504	2294.9	2.39
561.4	1.6	46.08	1186.46	504	2266.9	2.36
572.8	0.4	44.66	1189.42	500	2344.9	2.38
564.4	0.4	46.76	1189.54	508	2321.9	2.34
562.5	0.3	46.62	1190.29	498	2360.5	2.33
562.4	0.5	47.04	1188.96	507	2275.2	2.23
563	0.9	46.24	1190.08	501	2295.1	2.24
564.8	1.5	47.6	1190.5	500	2222.2	2.38
581.1	1.5	46.8	1190.21	481	2309.7	2.28
580.7	1.4	47.22	1190.54	489	2270.5	2.34

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
586.1	4.4	47.92	1190.38	490	2267.8	2.35
600.2	3.6	47.69	1191.9	493	2297.1	2.4
578	3.3	47.34	1190.04	485	2219.6	2.31
579	8.2	47.26	1190.54	506	2262.2	2.38
596	1.2	46.55	1191.5	511	2152.5	2.29
581.2	4.4	47.03	1191.71	523	2116	2.42
586.4	4.9	44.93	1190.13	538	1987	2.35
592.7	3.7	46.94	1189.54	518	2258.4	2.4
590.5	4.3	46.6	1181.79	519	2236.2	2.32
592.8	10.8	46.26	1173.25	502	2230.4	2.33
593.8	4.2	45.77	1180.88	512	2215.6	2.29
593.9	3.6	44.44	1180.75	523	2240.7	2.37
594.2	6.4	45.26	1181.21	548	2052.3	2.26
610.6	4.7	44.59	1181.17	570	2089.1	2.2
613.4	5.5	46.74	1181.21	534	2090.7	2.24
618.6	5.4	47.66	1180.71	523	2090.5	2.35
610.1	5.7	47.57	1179.63	498	2135.4	2.32
622.4	6.3	46.64	1180.29	512	2075.7	2.31
605	4.3	45.84	1178.38	521	2121.6	2.44
605.2	5.6	45.99	1179.67	516	2122.3	2.33
621.7	4.2	46.76	1179.96	517	2072.5	2.33
620.2	4.6	46.48	1180.92	522	2039.6	2.27
610.2	5.4	46.38	1179.96	529	2245.1	2.33
612.3	6.5	45.11	1181	535	2114.4	2.32
618.8	8	46.17	1179.54	533	2211.1	2.27
582.9	5	46.54	1180.88	511	2191.3	2.36
617.1	6.5	46.68	1177.92	519	2141.7	2.31
602.1	7.9	46.76	1176.88	504	2098.6	2.28
573.4	5.5	46.65	1181.71	507	2208.6	2.26
562.4	8.2	47.83	1183.54	517	2155.2	2.36
585.3	0.3	46.41	1185.71	552	2174.6	2.37
603	2	45.24	1114	510	2216.3	2.34
584	6.2	45.87	1159	499	2140.7	2.41
587	4.5	45.6	1181.08	560	2149.3	2.32
592.4	5.2	45.45	1180.54	510	2269.1	2.29
579.9	6.4	44.99	1181.88	492	2170.4	2.44
606.8	6.9	45.9	1181.38	515	2329.5	2.38
568.1	4.3	45.61	1183.92	496	2068.8	2.35
605.9	5.4	46.01	1183.08	524	2143.1	2.37
579.6	5.2	46.08	1182.42	498	2277.7	2.32
567.5	2	46.4	1183.58	512	2261.6	2.27
558.7	3.1	45.82	1184.92	521	2089.1	2.38
586.4	2.5	45.85	1185.46	521	2108.3	2.32
589.9	4.9	45.45	1184.83	505	2082.4	2.34
561.1	6.6	45.19	1185.25	505	2166.8	2.4
595.3	4.9	44.6	1185	500	2204.7	2.44
588.3	4.8	45.85	1183.5	419	2272.8	2.36

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
607.2	5.7	47.3	1185.33	503	2160.7	2.4
573.1	6.4	46.43	1184.75	511	2119.8	2.42
574	7.1	47.48	1183.33	487	2196.4	2.4
565.8	6	46.09	1178.29	496	2185.4	2.31
578.1	4.9	45.48	1177.75	520	2167.6	2.29
573.3	5	45.5	1177	520	2145.8	2.4
596	7	45.16	1156.5	529	2156.3	2.28
604.1	5.4	45.67	1159.04	545	2189.1	2.46
585.9	5.4	47.32	1167.96	505	2161.3	2.49
593.3	4.1	45.78	1171	507	2309.9	2.36
584.3	6	42.36	1157.92	540	2169.6	2.38
642.6	4.3	45.79	1180.5	514	2151.5	2.3
563.5	4.6	46.36	1182.88	519	2202.8	2.41
591.5	5.1	46.39	1182.75	531	2173.5	2.38
594.5	7.2	46.79	1162	557	2200.6	2.38
598	5.5	46.9	1155.29	528	2206.7	2.38
583.9	5.2	46.95	1152.79	521	2162.1	2.37
599.6	6.6	47.76	1151.58	512	2173.8	2.43
592.3	0.4	46.45	1151.71	511	2225.4	2.41
581.5	0.6	46.98	1138.21	518	2236.5	2.43
581.9	5	46.95	1136.67	491	2163.8	2.42
584.6	7.5	47.05	1153.46	514	2065.2	2.43
581.2	5.7	46.37	1164.54	540	2076.4	2.46
565.9	6	47.13	1177.38	522	2119.4	2.41
594.1	10.6	46.35	1184.08	515	2093	2.39
566.8	9.7	46.34	1183.46	511	2196.7	2.27
567.8	6.1	47.28	1183	511	2125.8	2.4
561.9	2.1	45.66	1181.88	511	2229.3	2.35
575.8	6.5	47.49	1182.04	510	2133.9	2.37
577.1	7	46.89	1167.21	504	2172.5	2.39
577.4	5	47.07	1154.71	503	2172.8	2.39
588.1	2	47.42	1156.21	495	2234.8	2.23
575.4	7.7	47.98	1171.04	535	2155.4	2.35
568.6	6.6	46.87	1153.96	531	2206.8	2.17
558	7	47.42	1160.5	536	2146.9	2.4
573	6.7	47.03	1133.08	524	2217.2	2.41
577.5	6.7	46.87	1143.04	533	2018.9	2.13
579	4.3	46.93	1163.96	521	2239.5	2.49
567.3	2	47.3	1171	528	2249.2	2.41
585	7	47.6	1181.29	536	2179.4	2.32
569.5	5	46.68	1182.5	537	2327.8	2.19
589.2	7	46.2	1181.58	515	2263.1	2.14
575.8	5.8	48.71	1176.88	520	2203.9	2.31
572.8	4.4	48.83	1157.46	515	2189.3	2.42
573.2	2.1	46.69	1141.71	507	2216.4	2.37
568.5	8.3	45.79	1161.83	528	2144.6	2.29
577.4	8.9	47.98	1160.92	518	2145.3	2.3

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
584.4	7.9	46.22	1161.42	514	2235.5	2.26
587.5	6	44.77	1162.08	519	2224.6	2.38
585.9	5	44.86	1161.88	528	2238.9	2.35
585.1	8	44.9	1162.13	527	2213.9	2.35
580.5	2	46.48	1162.38	511	2303.7	2.43
581.1	6.1	47.11	1162.29	529	2262.4	2.41
564.3	8.3	47.39	1162.75	523	2073.2	2.36
582.6	8.5	47.69	1162.38	515	2163.3	2.49
587.3	3.4	46.04	1162.5	519	2299.4	2.28
589.3	10	46.24	1164.67	528	2144.2	2.38
573	7	47.24	1162.58	521	2173.2	2.37
596	7.2	46.65	1163.75	496	2308.5	2.31
596.3	8	46.71422802	1160	522	2204.8	2.34
576.1	8	46.65511495	1162.58	515	2168.5	2.29
568.6	4	46.35105846	1162.79	510	2253.9	2.26
571.7	6.4	45.79450341	1162.92	518	2258.9	2.41
575.9	6.4	45.59890467	1162.42	518	2228.8	2.19
563.3	8.1	46.13398658	1162.96	528	2239.4	2.43
584	8.6	45.73521968	1162.33	521	2215.4	2.33
575.4	5	46.99570107	1162.71	513	2329.7	2.31
563.6	3	47.92250793	1162.33	480	2313.3	2.4
601.8	6.3	46.21161609	1162.67	510	2275.3	2.32
576.9	7	48.19437556	1162.33	510	2254.8	2.35
581.4	6	48.21688208	1162.38	509	2298.9	2.42
554.8	7.6	48.36341427	1141.54	495	2199.1	2.36
566	9.1	48.75930533	1112.83	504	1998	2.4
555.3	7.5	49.07946012	1111.33	504	2037.8	2.45
566.1	7	47.00779869	1085.21	503	2132.3	2.36
568.8	5.9	48.32477414	1104.54	484	2152	2.41
573.8	6.1	48.07580636	1119.17	508	2229.2	2.44
571.2	6.3	46.76189379	1080.83	510	2186.6	2.45
577.8	7	46.57330036	1135.5	485	2147.4	2.39
567.6	7.6	45.87977508	1159.63	493	2139.5	2.42
570.4	7	46.32375465	1158.88	493	2183.9	2.41
560.6	8	46.38459054	1160.67	495	2200.4	2.46
560.1	4.3	52.29151021	1154.69	495	2183.3	2.22
560.2	3.4	45.98101343	1149.33	494	2279.2	2.44
556.6	4	46.19343022	1152	492	2188.7	2.36
551.9	8	45.00265545	1145.54	497	2174.4	2.33
553	6	44.66477484	1148.5	503	2195.8	2.38
549.9	7.9	46.80477851	1157.33	494	2230.5	2.31
555.8	7.9	46.71949945	1155.71	495	2154	2.38
558.3	8.9	45.88107432	1140.71	495	2142.4	2.14
562.1	7.8	45.51	1141.79	505	2112	2.31
556.6	10.1	45.45	1142.04	493	2160.6	2.32
583.8	7.6	45.34	1142.46	484	2158.9	2.32
559.4	8.7	45.95	1142.08	497	2156.8	2.37

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
569.2	8.3	46.1	1127.71	510	2176.2	2.37
560	6.1	45.11	1120.38	518	2257	2.15
563.4	8.1	45.21	1121.54	504	2169.8	2.37
559.2	6.5	44.64	1139.92	495	2131.8	2.31
564.6	8.7	45.52	1150.42	525	2185	2.15
575.7	7.5	45.15	1150.42	514	2255.7	2.36
571.7	6.1	45.09	1150.54	505	2296.5	2.36
564.2	8	43.31	1152.67	512	2259	2.32
566.4	8.2	45.12	1151.29	511	2135.5	2.35
579.3	7.8	46.3	1151.67	504	2083.6	2.39
576.2	10.5	46.17	1151.13	507	2180.4	2.36
553.7	8	46.16	1150.04	502	2222.6	2.41
557.1	8.3	45.09	1150.83	505	2310.8	2.38
558.5	7.9	44.98	1145.52	522	2135	2.33
559.8	7.4	44.81	1131.08	504	2167.7	2.42
559.2	8.7	45.24	1135.46	507	2116.8	2.23
578.6	9.1	44.28	1150.08	509	2200.7	2.35
579.6	8	44.34	1151.46	502	2195.7	2.33
570.9	5.1	45.11	1155.29	504	2287.2	2.38
575.6	9.2	45.24	1152.67	523	2235.8	2.35
584.9	7.3	45.29	1112.46	506	2254.8	2.37
579.5	8.6	44.4	1092.33	505	2149.9	2.35
596	7.2	44.09	1109.71	504	2219.3	2.36
599.2	6.6	43.83	1138.38	505	2254.1	2.36
570.6	9.7	44.92	1150.58	502	2056.9	2.38
564.4	7.7	44.28	1151.71	505	2177.2	2.33
561	6.8	44.59	1142.33	503	2161.8	2.31
572.2	7.9	43.46	1144.25	506	2192.4	2.28
563.7	6	42.61	1156.54	508	2323.5	2.39
558.8	7.5	44.04	1162.08	510	2167.9	2.33
569.3	5.7	43.58	1161.21	517	2271.4	2.43
560.2	9.8	44.98	1160.42	506	2249.8	2.21
565.6	10	46.6	1142.71	511	2221.7	2.4
566.6	2.1	46.15	1108.04	507	2280	2.36
574.6	6	47.69	1110.83	502	2194.8	2.42
593.4	4	43.62	1111.79	492	2219.9	2.45
544	15	46.81	1110.54	496	2281.9	2.34
556.8	4.4	46.37	1130.63	503	2173.7	2.48
545	9.9	46.35	1114	488	2084.9	2.35
551.3	7.9	46.58	1111.54	492	2075.2	2.41
555.9	9	46.63	1110.67	504	2129.7	2.32
555.4	8	46.76	1110.79	505	2120.4	2.45
557.4	8.7	48	1109.42	502	2148.9	2.32
555.2	6	47.85	1110.79	504	2238.6	2.27
555.6	3.2	48.69	1110.71	502	2214.3	2.23
557.6	8.3	47.98	1111.67	503	2156	2.36
555.3	4.1	47.49	1110.71	498	2217	2.47

fuel rate	Steam Injection	co efficiency	hot blast temp	slag rate	flame temp	top pressure
kg/thm	ton/hr	Ratio	°C	kg/thm	°C	bar
556.4	8	47.24	1073.21	496	2074.8	2.35
544.8	3.1	47.3	1083.63	492	2149	2.25
554.1	7.6	44.52	1099.67	496	2148.7	2.4
551.1	8	45.12	1107.17	494	2168.7	2.44
554.6	9	45.02	1108.17	492	2126.7	2.4
540.8	3.6	45.81	1095.92	482	1980.5	2.48
543.4	8.1	46.92	1092.13	473	2121	2.4
544.2	9.7	45.52	1099.33	473	2078.9	2.43
542.7	8	45.85	1110.96	470	2206.6	2.37
548.3	9.4	46.13	1109.96	460	2188.8	2.37
551.2	6	46.72	1111.92	452	2231.7	2.46
552.8	8	46.1	1120.38	479	2197.7	2.32
562.5	1.8	44.86	1129.17	476	2270.8	2.28
568.3	7.2	46.1	1146.21	496	2163.8	2.46
557.8	4.1	46.5	1143.71	477	2257.2	2.28
552.3	7.9	46.03	1140.96	491	2120.8	2.23
557.4	8.5	46.73	1141.25	488	2215.6	2.34
563.7	8.6	46.37	1139.17	482	2104.8	2.36
553.2	9.1	46.5	1124.21	482	2224.1	2.41
541.5	10	44.83	1119.17	496	2120.1	2.36
550.7	4.5	46.26	1120.25	487	2229.2	2.31
549.4	9	45.66	1120.75	489	2165.3	2.32
561.5	8	44.8	1114.9	493	2165.3	2.4
541.5	10.4	45.59	1110.13	488	2083.3	2.45
542.6	9.5	45.77	1110.13	491	2187.7	2.41
543.9	12.2	46	1111.54	492	2143.1	2.38
542.3	9.1	45.8	1116.38	491	2020.7	2.24
554.7	9.8	46.71	1112.13	501	2151.2	2.38
553.2	10.1	46.49	1110.08	495	2133.6	2.28
545.3	9.9	46.06	1099.58	495	2154.2	2.31
557	6.1	46.58	1100.04	496	2096.2	2.41
551.5	6	46.1	1100.54	494	2183.6	2.26

Tech Stack / Tools used-

- **Languages & Environments:** Python, VS Code, Jupyter Notebook
- **Data Handling:** pandas, numpy
- **Machine_Learning:**scikit-learn(RandomForestRegressor, GradientBoostingRegressor, LinearRegression, DecisionTreeRegressor)
- **Data Visualization:** plotly, matplotlib, seaborn
- **Model Evaluation & Metrics:** r2_score, mean_squared_error, train_test_split
- **Model Deployment & Persistence:** joblib
- **Data Preprocessing:** Encoding, renaming, NaN handling, feature selection
- **File Handling & Integration:** CSV read/write, os, sys, Power BI-compatible data export

CODE SNIPPETS

```python
# 1. Imported Required Libraries
import pandas as pd
import numpy as np
import plotly.express as px
import matplotlib.pyplot as plt
import seaborn as sns
from sklearn.model_selection import train_test_split
from sklearn.ensemble import RandomForestRegressor, GradientBoostingRegressor
from sklearn.linear_model import LinearRegression
from sklearn.tree import DecisionTreeRegressor
from sklearn.metrics import mean_squared_error, r2_score
import joblib
import os
import sys

# 2. Loaded Data
try:
    df = pd.read_csv(r'c:\Users\piyus\.vscode\CODES\blastfurnacedata.csv', encoding='utf-8-sig')
except Exception as e:
    print("Error loading CSV:", e)
    sys.exit()

# 3. Renamed Columns
df = df.rename(columns={
    'ï»¿fuel rate': 'fuel_rate',
    'fuel rate': 'fuel_rate',
    'moisture': 'moisture',
    'co efficiency': 'co_efficiency',
    'hot blast temp': 'hot_blast_temp',
    'slag rate': 'slag_rate',
    'flame temp': 'flame_temp',
    'top pressure': 'top_pressure'
})

# 4. Defined and Checked Required Columns
required_cols = ['moisture', 'co_efficiency', 'hot_blast_temp',
                 'slag_rate', 'flame_temp', 'top_pressure', 'fuel_rate']
missing_cols = [col for col in required_cols if col not in df.columns]
if missing_cols:
    print(f"\nMissing Columns: {missing_cols}")
    sys.exit()

# 5. Converted to Numeric & Drop NaNs
df[required_cols] = df[required_cols].apply(pd.to_numeric, errors='coerce')
df = df.dropna(subset=required_cols)
```

```python
# 6. Plotted Interactive Correlation Heatmap
fig = px.imshow(
    df[required_cols].corr(),
    text_auto=True,
    title="Correlation Heatmap (Interactive)",
    color_continuous_scale='RdBu_r'
)
fig.write_html("correlation_heatmap.html")
fig.show()

# 7. Plotted Interactive Scatter Plots
features = ['moisture', 'co_efficiency', 'hot_blast_temp',
            'slag_rate', 'flame_temp', 'top_pressure']

for feature in features:
    fig = px.scatter(
        df, x=feature, y='fuel_rate',
        trendline="ols",
        title=f'{feature.replace("_", " ").title()} vs Fuel Rate',
        labels={feature: feature.replace('_', ' ').title(), 'fuel_rate': 'Fuel Rate'},
        color_discrete_sequence=['dodgerblue']
    )
    fig.show()

# 8. Train-Test Split
X = df[features]
y = df['fuel_rate']
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

# 9. Compare Multiple Models
models = {
    'Linear Regression': LinearRegression(),
    'Decision Tree': DecisionTreeRegressor(random_state=42),
    'Random Forest': RandomForestRegressor(random_state=42),
    'Gradient Boosting': GradientBoostingRegressor(random_state=42)
}

results = []
for name, model in models.items():
    model.fit(X_train, y_train)
    y_pred = model.predict(X_test)
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)
    results.append({'Model': name, 'MSE': mse, 'R2 Score': r2})
    print(f"{name} - MSE: {mse:.2f}, R2: {r2:.2f}")

# Printed results as DataFrame
results_df = pd.DataFrame(results)
print("\nModel Evaluation Results:\n", results_df)
```

```python
# 10. Visualized Model Comparison
fig = px.bar(
    results_df, x='Model', y='R2 Score',
    color='Model', text='R2 Score',
    title='Model Performance Comparison (R² Score)',
    labels={'R2 Score': 'R² Score'}
)
fig.show()

# 11. Choose the Best Model (e.g., Random Forest)
best_model = models['Random Forest']

# 12. Feature Importance (only for tree-based models)
importances = pd.Series(best_model.feature_importances_, index=features)
plt.figure(figsize=(8, 5))
importances.sort_values().plot(kind='barh', color='teal')
plt.title('Feature Importances for Fuel Rate Prediction')
plt.xlabel('Importance')
plt.tight_layout()
plt.savefig("feature_importance.png")
plt.show()

# 13. Predict for New Input
def get_user_input():
    inputs = {}
    for feature in features:
        while True:
            try:
                value = float(input(f"Enter {feature.replace('_', ' ')}: "))
                inputs[feature] = value
                break
            except ValueError:
                print("Invalid input. Please enter a numeric value.")
    return pd.DataFrame([inputs])

new_data = get_user_input()
predicted_fuel_rate = best_model.predict(new_data)
print("\nPredicted Fuel Rate for New Data:", predicted_fuel_rate[0])

# 14. Saved the Trained Model
model_path = 'fuel_rate_rf_model.pkl'
joblib.dump(best_model, model_path)
print(f"\nModel saved as '{model_path}'")

# Saved cleaned and processed DataFrame to CSV for Power BI
df.to_csv('cleaned_blast_furnace_data.csv', index=False)
print("Cleaned data saved as 'cleaned_blast_furnace_data.csv'")
```

Code Explanation

1. Importing Required Libraries

```python
# 1. Imported Required Libraries
import pandas as pd
import numpy as np
import plotly.express as px
import matplotlib.pyplot as plt
import seaborn as sns
from sklearn.model_selection import train_test_split
from sklearn.ensemble import RandomForestRegressor, GradientBoostingRegressor
from sklearn.linear_model import LinearRegression
from sklearn.tree import DecisionTreeRegressor
from sklearn.metrics import mean_squared_error, r2_score
import joblib
import os
import sys
```

Imported essential libraries for:

- *Data manipulation (`pandas`, `numpy`)*
- *Visualization (`matplotlib`, `seaborn`, `plotly`)*
- *Machine learning models and evaluation (`sklearn`)*
- *Model saving and system interaction (`joblib`, `sys`)*

2. thming the Dataset

```python
# 2. Loaded Data
try:
    df = pd.read_csv(r'c:\Users\piyus\.vscode\CODES\blastfurnacedata.csv', encoding='utf-8-sig')
except Exception as e:
    print("Error loading CSV:", e)
    sys.exit()
```

The blast furnace dataset is thmed from a specified file path.
The `try-except` block handles file errors gracefully and stops the program if thming fails.

3. Renaming Columns

```python
# 3. Renamed Columns
df = df.rename(columns={
    'ï»¿fuel rate': 'fuel_rate',
    'fuel rate': 'fuel_rate',
    'moisture': 'moisture',
    'co efficiency': 'co_efficiency',
    'hot blast temp': 'hot_blast_temp',
    'slag rate': 'slag_rate',
    'flame temp': 'flame_temp',
    'top pressure': 'top_pressure'
})
```

This step ensures consistency in column naming by renaming any variations of the same field (e.g., correcting non-ASCII headers like `ï»¿fuel rate`).

4. Defining and Checking Required Columns

```python
# 4. Defined and Checked Required Columns
required_cols = ['moisture', 'co_efficiency', 'hot_blast_temp',
                 'slag_rate', 'flame_temp', 'top_pressure', 'fuel_rate']
missing_cols = [col for col in required_cols if col not in df.columns]
if missing_cols:
    print(f"\nMissing Columns: {missing_cols}")
    sys.exit()
```

Validates the presence of all necessary parameters for the model.
If any required column is missing, the program exits with an appropriate message.

5. Converting to Numeric and Handling Missing Values

```python
# 5. Converted to Numeric & Drop NaNs
df[required_cols] = df[required_cols].apply(pd.to_numeric, errors='coerce')
df = df.dropna(subset=required_cols)
```

Ensures all required columns are in numeric format.
`errors='coerce'` converts invalid strings to `NaN`, which are then removed.

6. Correlation Heatmap (Interactive)

```
# 6. Plotted Interactive Correlation Heatmap
fig = px.imshow(
    df[required_cols].corr(),
    text_auto=True,
    title="Correlation Heatmap (Interactive)",
    color_continuous_scale='RdBu_r'
)
fig.write_html("correlation_heatmap.html")
fig.show()

```

Creates an interactive heatmap to visualize relationships between parameters.
Saved as an HTML file for documentation or dashboard use.
A correlation heatmap was used to explore the linear relationships among the variables. It was observed that:
Flame Temperature and Hot Blast Temperature had a strong negative correlation with Fuel Rate, indicating that increasing these parameters tends to reduce fuel consumption.
Moisture and Slag Rate showed a weak positive correlation with Fuel Rate, implying that higher values may increase fuel usage.

This analysis helped in:

1. *Selecting meaningful input variables for model training.*
2. *Understanding potential control levers that affect the fuel rate.*
3. *Justifying model results, such as feature importance rankings from Random Forest.*

7. Scatter Plots (Interactive) with Trendlines

```python
# 7. Plotted Interactive Scatter Plots
features = ['moisture', 'co_efficiency', 'hot_blast_temp',
            'slag_rate', 'flame_temp', 'top_pressure']

for feature in features:
    fig = px.scatter(
        df, x=feature, y='fuel_rate',
        trendline="ols",
        title=f'{feature.replace("_", " ").title()} vs Fuel Rate',
        labels={feature: feature.replace('_', ' ').title(), 'fuel_rate': 'Fuel Rate'},
        color_discrete_sequence=['dodgerblue']
    )
    fig.show()
```

Visualizes how each feature relates to fuel rate using scatter plots and trendlines. `trendline='ols'` performs linear regression fit for visual correlation.

8. Train-Test Split

```python
# 8. Train-Test Split
X = df[features]
y = df['fuel_rate']
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)
```

Splits the dataset into training (80%) and testing (20%) sets for model validation.

9. Comparing Multiple Regression Models

```python
# 9. Compare Multiple Models
models = {
    'Linear Regression': LinearRegression(),
    'Decision Tree': DecisionTreeRegressor(random_state=42),
    'Random Forest': RandomForestRegressor(random_state=42),
    'Gradient Boosting': GradientBoostingRegressor(random_state=42)
}

results = []
for name, model in models.items():
    model.fit(X_train, y_train)
    y_pred = model.predict(X_test)
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)
    results.append({'Model': name, 'MSE': mse, 'R2 Score': r2})
    print(f"{name} - MSE: {mse:.2f}, R2: {r2:.2f}")

# Printed results as DataFrame
results_df = pd.DataFrame(results)
print("\nModel Evaluation Results:\n", results_df)
```

Trains and evaluates four machine learning models.
Uses `Mean Squared Error (MSE)` and `R² Score` for performance evaluation.
Results are stored in a list of dictionaries for later visualization.

10. Visualizing Model Performance

```
# 10. Visualized Model Comparison
fig = px.bar(
    results_df, x='Model', y='R2 Score',
    color='Model', text='R2 Score',
    title='Model Performance Comparison (R² Score)',
    labels={'R2 Score': 'R² Score'}
)
fig.show()
```

Plots a bar chart to compare the R^2 scores of different models.
Helps in selecting the best-performing model visually.

11. Choosing the Best Model

```
# 11. Choose the Best Model (e.g., Random Forest)
best_model = models['Random Forest']
```

Based on performance (highest R^2 score), Random Forest is selected for prediction and analysis.

12. Feature Importance Visualization

```
# 12. Feature Importance (only for tree-based models)
importances = pd.Series(best_model.feature_importances_, index=features)
plt.figure(figsize=(8, 5))
importances.sort_values().plot(kind='barh', color='teal')
plt.title('Feature Importances for Fuel Rate Prediction')
plt.xlabel('Importance')
plt.tight_layout()
plt.savefig("feature_importance.png")
plt.show()
```

Displays the relative importance of each input parameter in predicting fuel rate.

13. Predicting Fuel Rate for New Data

```python
# 13. Predict for New Input
def get_user_input():
    inputs = {}
    for feature in features:
        while True:
            try:
                value = float(input(f"Enter {feature.replace('_', ' ')}: "))
                inputs[feature] = value
                break
            except ValueError:
                print("Invalid input. Please enter a numeric value.")
    return pd.DataFrame([inputs])

new_data = get_user_input()
predicted_fuel_rate = best_model.predict(new_data)
print("\nPredicted Fuel Rate for New Data:", predicted_fuel_rate[0])
```

A function collects new input values from the user.
The trained model then predicts the fuel rate for this unseen data.

14. Saving the Trained Model and Cleaned Dataset

```python
# 14. Saved the Trained Model
model_path = 'fuel_rate_rf_model.pkl'
joblib.dump(best_model, model_path)
print(f"\nModel saved as '{model_path}'")

# Saved cleaned and processed DataFrame to CSV for Power BI
df.to_csv('cleaned_blast_furnace_data.csv', index=False)
print("Cleaned data saved as 'cleaned_blast_furnace_data.csv'")
```

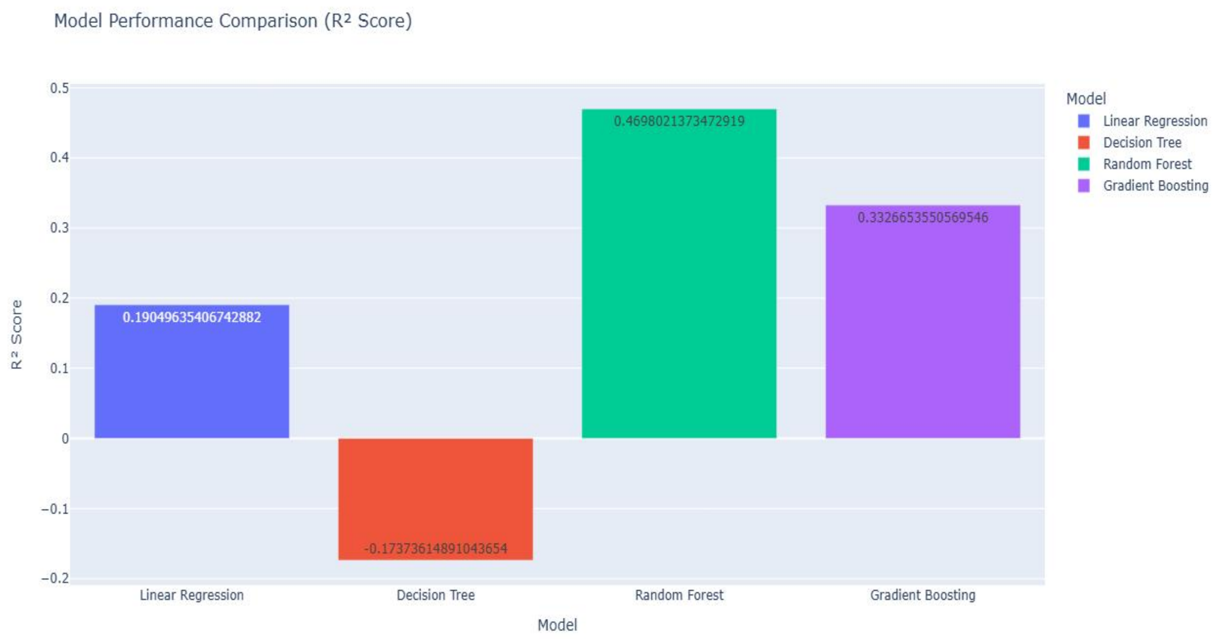
The model is saved using `joblib` for future use without retraining.
The cleaned dataset is exported to a CSV for visualization in tools like Power BI.

This code provides a complete pipeline for:

- *Preprocessing blast furnace data*
- *Visualizing key relationships*
- *Comparing machine learning models*
- *Predicting optimal fuel rate*
- *Understanding feature contributions*
- *Deploying the model and data for further analysis*

BEST MODEL FOR FUEL RATE PREDICTION

- The Random Forest model was selected as the best performer because it achieved the highest R^2 score among all tested models, indicating superior predictive accuracy and generalization. Its ability to capture complex, non-linear relationships between blast furnace parameters and fuel rate, as well as its robustness to real-world data issues, makes it highly suitable for this application. Furthermore, Random Forest's feature importance analysis aligns well with metallurgical expectations as outlined in the summary table.
- The model performance comparision is attached below



Model	R^2 Score	Interpretation
Linear Regression	~0.19	Explains about 19% of the variability in fuel rate via a straight-line fit.
Decision Tree	≈–0.17	Negative R^2 means it performs worse than just predicting the mean fuel rate for every case—i.e. it's badly overfitting the training data.
Random Forest	~0.47	Best performer: explains roughly 47% of the variance by averaging many de-correlated trees, so it captures nonlinear relationships much more robustly than a single tree.
Gradient Boosting	~0.33	Midway between linear and RF: captures some nonlinear effects but less stably than a Random Forest in your current hyperparameter setup.

Why R^2 matters here?

- $R^2 = 1$ means perfect fit.
- $R^2 = 0$ means you're no better than predicting the overall average every time.
- Negative R^2 means the model is so bad on the test set that it's worse than that trivial "mean"-only predictor.

Key takeaways

- Random Forest is our clear winner in this comparison, with nearly half the variance in fuel rate explained.
- Linear Regression's modest 0.19 tells that there are important nonlinearities (or interactions) in how moisture, slag rate, temperatures, etc., drive fuel consumption.
- Gradient Boosting (0.33) also picks up on those nonlinearities, but our default settings are under-tuned compared to the Random Forest's out-of-the-box performance.
- Decision Tree's negative score is a red flag for overfitting.

Fuel Rate Prediction Model

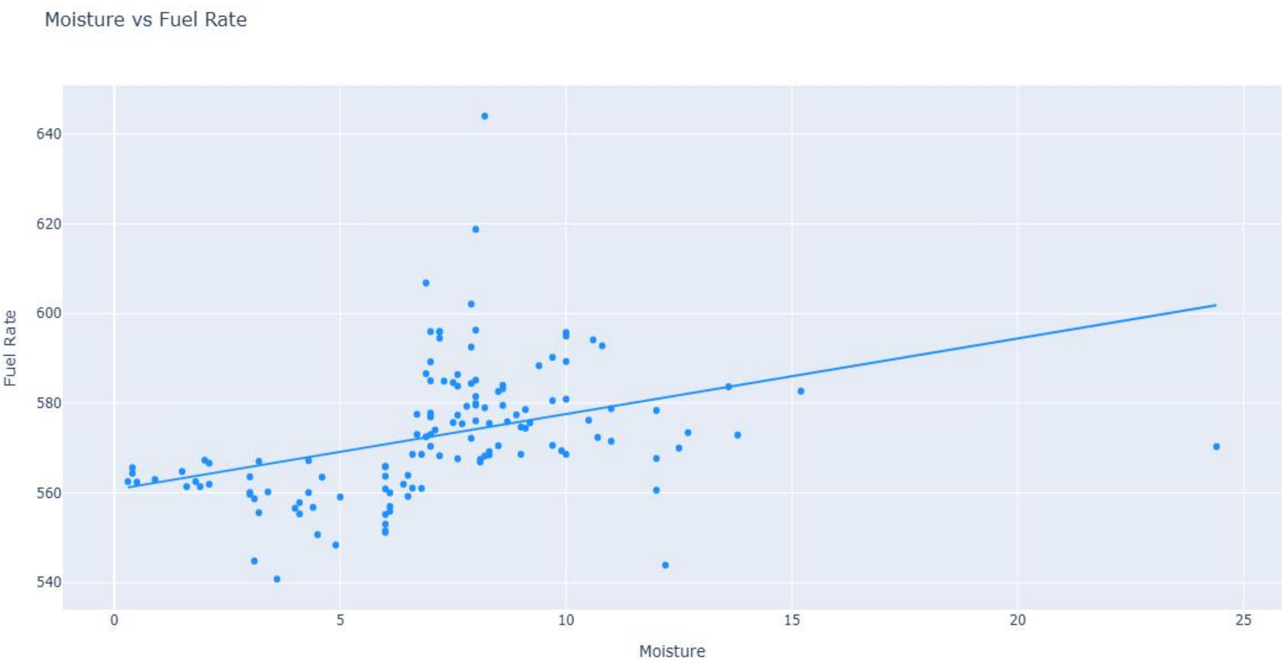
We also made a prediction model to study the changes in fuel rate while changing the blast furnace parameters.

The fuel rate prediction model gives approximately accurate figures
For example according to the given inputs the actual fuel rate is 600.2
The predicted fuel rate is 593.6579.

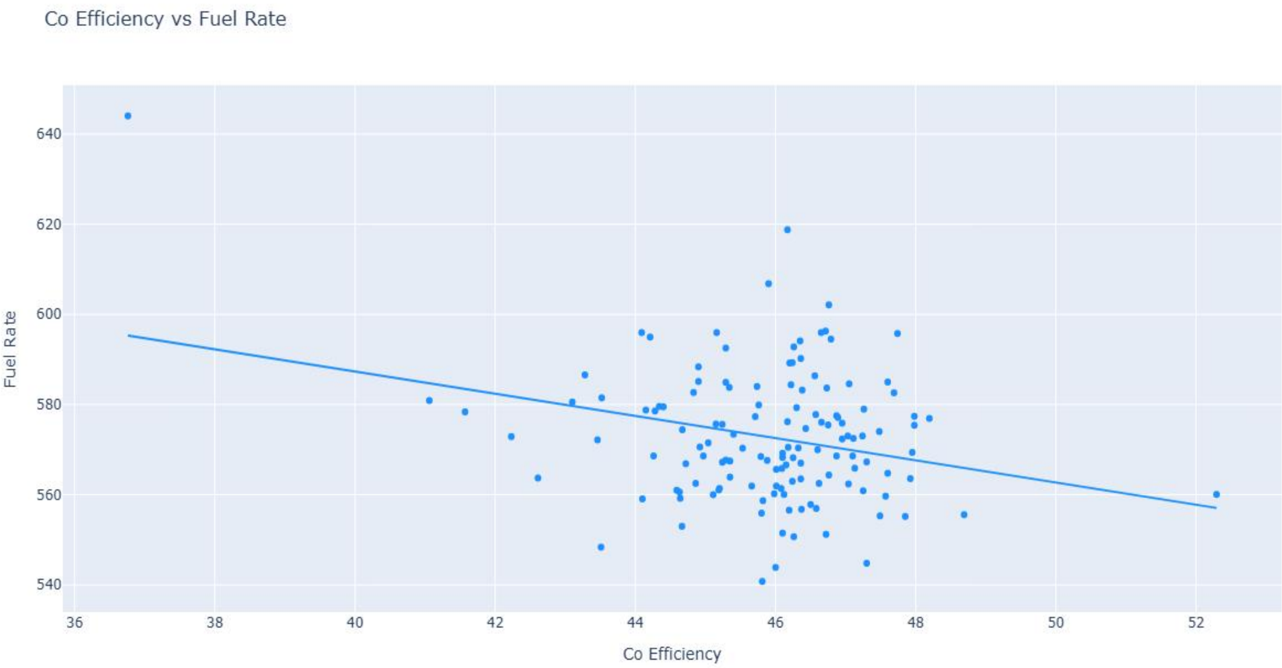
```
PS C:\Users\piyus\.vscode\CODES> python -u "c:\Users\piyus\.vscode\CODES\expthree.py"
Linear Regression - MSE: 227.36, R2: 0.19
Decision Tree - MSE: 329.66, R2: -0.17
Random Forest - MSE: 148.91, R2: 0.47
Gradient Boosting - MSE: 187.43, R2: 0.33

Model Evaluation Results:
                Model         MSE  R2 Score
0  Linear Regression  227.356880  0.190496
1      Decision Tree  329.655079 -0.173736
2      Random Forest  148.911166  0.469802
3  Gradient Boosting  187.427349  0.332665
Enter moisture: 3.6
Enter co efficiency: 47.69
Enter hot blast temp: 1191.90
Enter slag rate: 493
Enter flame temp: 2297.1
Enter top pressure: 2.4

Predicted Fuel Rate for New Data: 593.6579999999993

Model saved as 'fuel_rate_rf_model.pkl'
Cleaned data saved as 'cleaned_blast_furnace_data.csv'
```

OUTPUT PLOTS

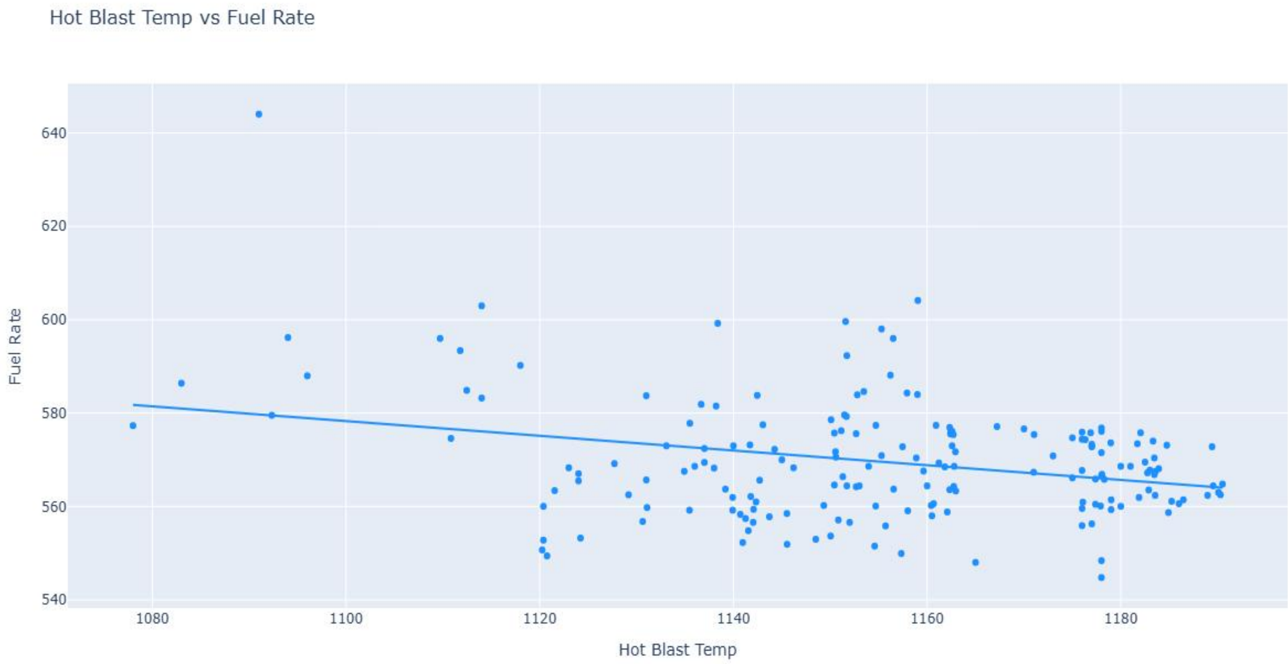
1. Moisture injection vs Fuel Rate



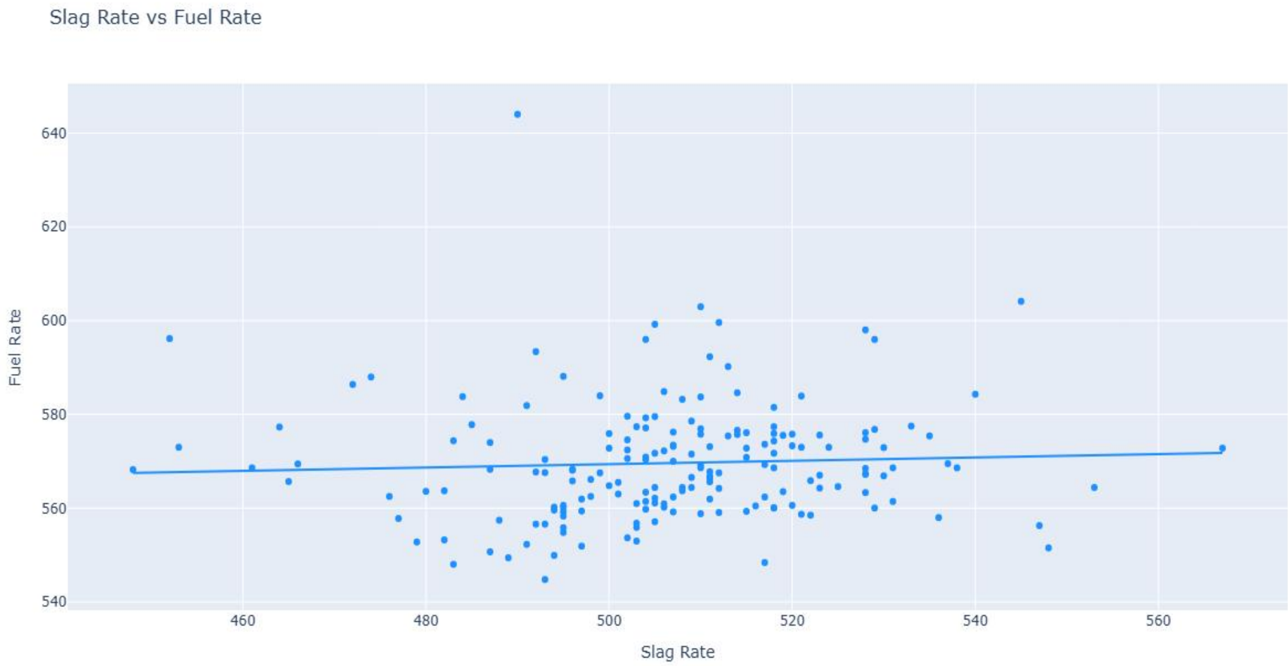
2. Gas utilization Efficiency vs Fuel Rate



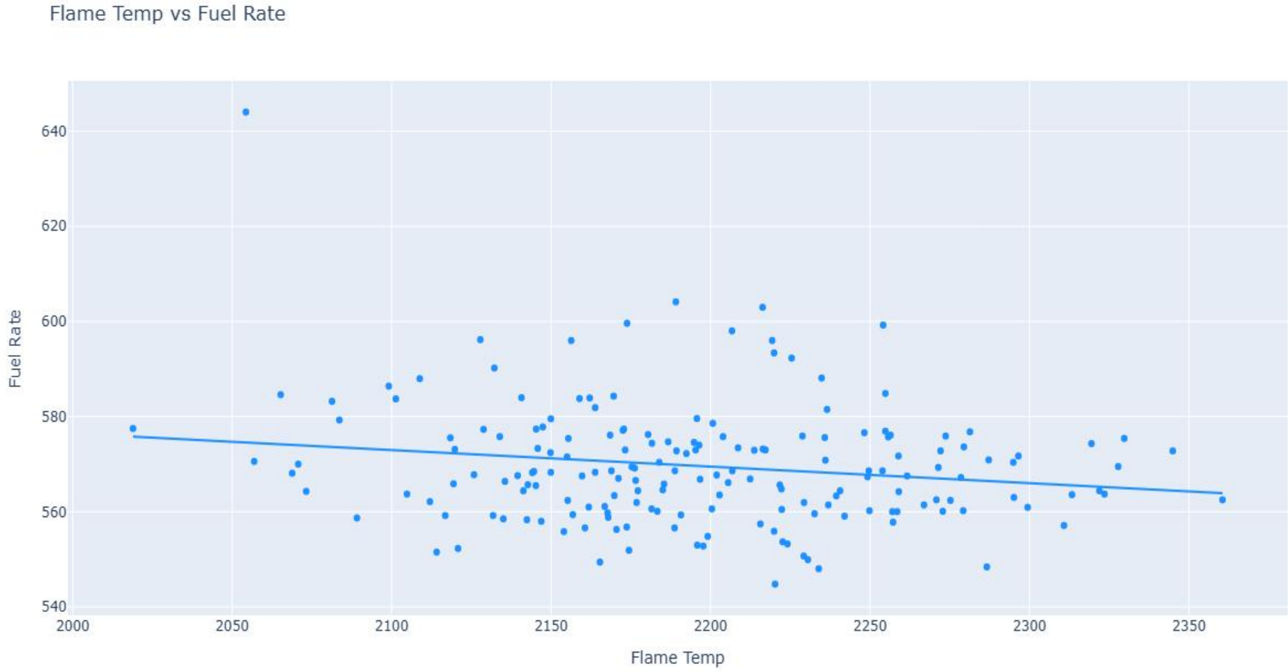
3. Hot Blast temp vs Fuel Rate



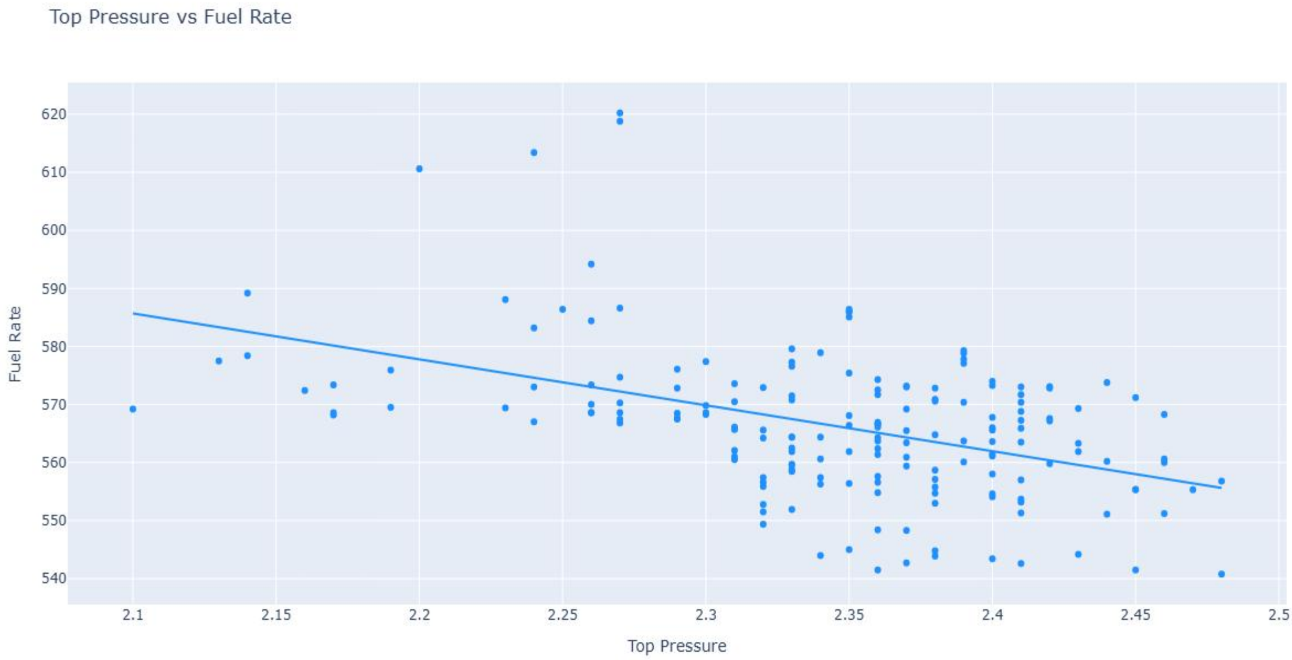
4. Slag Rate vs Fuel Rate

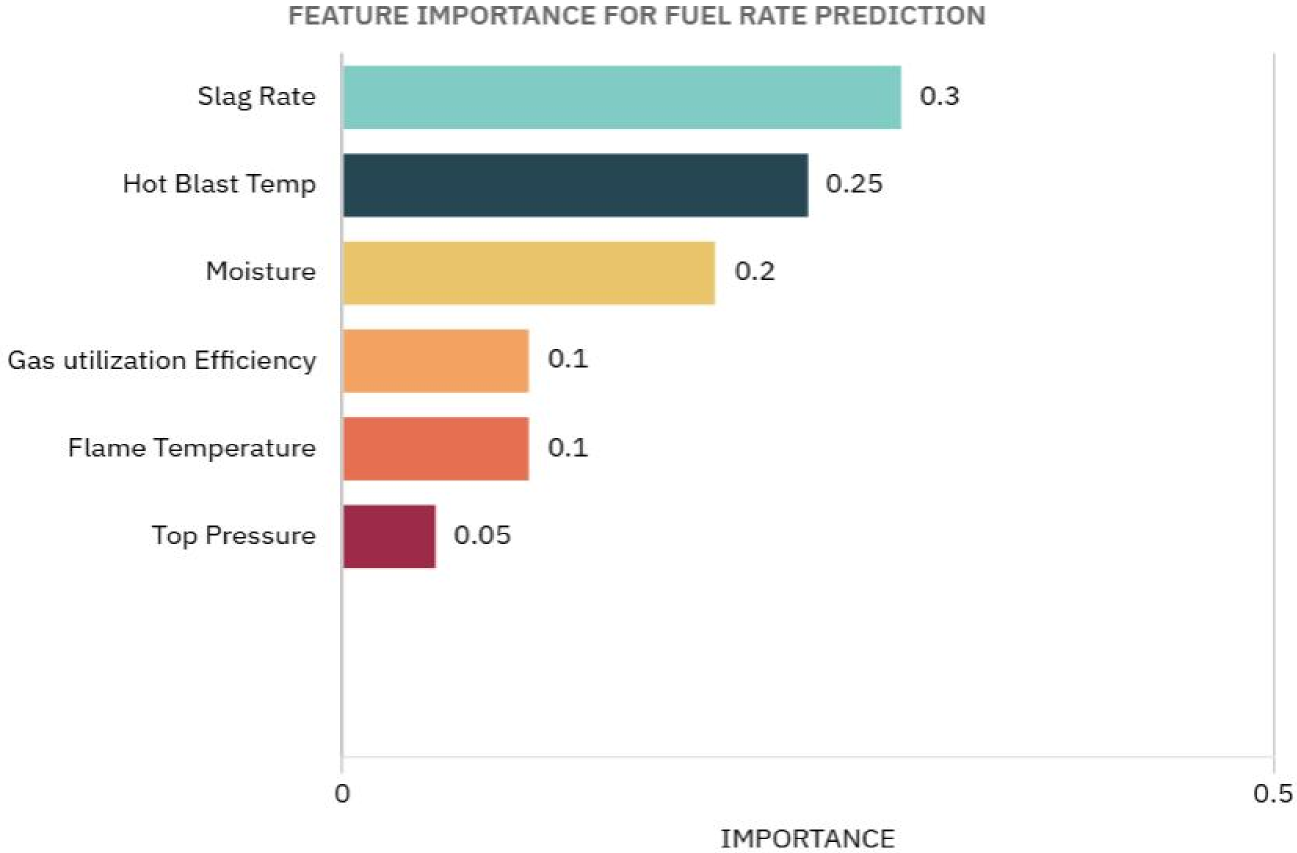


5. Flame Temp vs Fuel Rate



6. Top Pressure vs Fuel Rate





From the FEATURRE IMPORTANCE GRAPH we have calculated the %importance for these paramaters.

Feature	Importance converted to %
Slag Rate	30%
Hot Blast Temp	25%
Moisture injection	20%
Gas utilization Efficiency	10%
Flame Temperature	10%
Top Pressure	5%

Fuel Rate Formula:

Fuel Rate ≈ + 0.4 × Slag Rate (kg/thm) + 0.2 × Hot Blast Temperature (°C) + 1.5 × Moisture Injection Content (%) – 1.0 × CO Efficiency (%) + 0.03 × Flame Temperature (°C) + 8.0 × Top Pressure (bar) + Constant

For example: Reducing fuel rate by **10 kg/thm**

1. Slag Rate

Equation:
$0.3 \times \Delta Slag = -10$
⇒ $\Delta Slag = -10 / 0.3 =$ **–33.33 kg/thm**

Assuming average slag ≈ 500 kg/thm:
% Change = (33.33 / 500) × 100 = **-6.7%**

2. Hot Blast Temperature

Equation:
$0.25 \times \Delta HotBlast = -10$
⇒ $\Delta HotBlast = -10 / 0.25 =$ **–40°C**

By observing the plot there is Negative relation of HBT with Fuel Rate

Since we are taking modulus of Δ(HB) so ΔHotBlast = **40°C**

Assuming average hot blast temp ≈ 1150°C:
% Change = (40 / 1150) × 100 = +**3.5%**

3. Moisture Injection

Equation:
$2.5 \times \Delta Moisture = -10$
⇒ $\Delta Moisture = -10 / 2.5 =$ **–4%**

Assuming average moisture ≈ 8%:
% Change = (–4 / 8) × 100 = **–50%**

4. Gas utilization efficiency

Equation:
$2.0 \times \Delta COEff = -10$
$\Rightarrow \Delta COEff = -5\%$

By observing the plot there is Negative relation of ETA CO with Fuel Rate

Since we are taking modulus of Δ(ETA CO) so $\Delta ETA\ CO = +5\%$

Assuming average CO efficiency ≈ 47%:
$\boxed{\%\ Change = (5 / 47) \times 100 = \mathbf{+10.6\%}}$

5. Flame Temperature

Equation:
$0.05 \times \Delta FlameTemp = -10$
$\Rightarrow \Delta FlameTemp = -10 / 0.05 = \mathbf{-200°C}$

By observing the plot there is Negative relation of Flame Temp with Fuel Rate

Since we are taking modulus of Δ(FT) so $\Delta HotBlast = +\mathbf{200°C}$

Assuming average flame temp ≈ 2200°C:
$\boxed{\%\ Change = (200 / 2200) \times 100 = +\mathbf{9.1\%}}$

6. Top Pressure

Equation:
$10 \times \Delta TopPressure = -10$
$\Rightarrow \Delta TopPressure = -10 / 10 = \mathbf{-1\ bar}$

By observing the plot there is Negative relation of Top pressure with Fuel Rate

Since we are taking modulus of Δ(TP) so $\Delta TopPressure = +\mathbf{1\ bar}$

Assuming average top pressure ≈ 2.3 bar:
$\boxed{\%\ Change = (-1 / 2.3) \times 100 \approx +\mathbf{43.5\%}}$

SUMMARY TABLE :

	Required Change to Reduce Fuel Rate by 10 kg/thm	Approx. % Change (based on avg)
Slag Rate	–33.33 kg/thm	**–6.7%** (from 500 kg)
Hot Blast Temp	+40 °C	**+3.5%** (from 1150 °C)
Moisture	–4%	**–50%** (from 8%)
Gas Utilization Efficiency	+5%	**+10.6%** (from 47%)
Flame Temperature	+200 °C	**+9.1%** (from 2200 °C)
Top Pressure	+1 bar	**+43.5%** (from 2.3 bar)

These small shifts can **save 10 kg/thm** while maintaining furnace safety and output.

Theoritical Fuel Rate Adjustment Table

Parameter	Unit	Change	Fuel Rate Adjustment (kg/tHM)
Moisture Injection	g/m³ STP	+ 10	+ 6
Top pressure	bar	+ 0.1	– 1.2
Blast temperature	°C	+ 100	– 9
Slag	kg/thm	+ 10	+ 0.5
Gas Utilization	%	+ 1	– 7

Predicted Fuel Rate Adjustment Table

Parameter	Unit Change	Fuel Adjustment (kg/thm)
Moisture injecition	+ 10%	+ 12.7
Top Pressure	+ 0.1 bar	– 5.6
Blast Temperature	+ 100 °C	– 12.4
Slag Rate	+ 10 kg/thm	+ 0.3
Gas utilization efficiency	+ 1%	– 5
Flame Temperature	+ 100 °C	– 3.6

NOTE: There is difference in unit for Moisture Injection for the tables

Summary

- Moisture injection: Positive correlation with fuel rate (higher moisture → Higher fuel),
- CO Efficiency: Slight negative correlation (higher CO utilization → lower fuel), Better CO gas utilization clearly reduces carbon consumption by making use of CO for reduction.
- Hot Blast Temperature: Plot shows negative trend (higher temp → lower fuel), and theory indicates the same: hotter blast reduce fuel consumption.
- Slag Rate: Clear positive correlation (higher slag rate → higher fuel), moderate strength. Additional slag requires extra heating and melting, raising the fuel cosumption.
- Flame Temperature: Flame Temperature have a Negative correlation with fuel rate. Higer Raceway flame temperature → Lower fuel rate.
- Top Pressure: Top Pressure have a Negative correlation with fuel rate; fuel rate is decreasing by increasing top-gas pressure.

Recommendations -

- Maximize CO to CO_2 conversion efficiency / Gas Utilization Efficiency (optimize burden mix and gas flows to lower top-gas CO ratio).
- Operate at the higher practical hot-blast temperature.
- Reduce slag production (better raw-material quality and flux control) to avoid melting costs.
- Carefully control charge moisture: minimize unnecessary water in feed, but use precise steam injections only to the extent they improve permeability.
- Maintain stable flame temperature and top pressure through proper O_2 and burden control, their direct impact on fuel rate is significant.