
OXYGEN - A VERSATILE TOOL TO ENHANCE CUPOLA OPERATIONS

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Abstract

Ever-increasing pressures from global cost competition and environmental regulations demand improvements of coke-based cupola iron melting operation on an on-going basis. Various options including oxygen, hot blast, secondary blast, water-cooled shell, blast dehumidification, selective charge-mix, coke sizing and quality, charging methods, etc. - all improve cupola operations. This paper discusses the flexibility that oxygen can provide to the cupola operators. Unlike several capital-intensive options, oxygen is a flexible tool, requiring minimal capital investment, and the operating cost depends on the oxygen intensity the operator chooses to apply at a given period depending on market demand and the objectives of using oxygen.

Starting from the traditional method of enriching the cupola blast with oxygen, the paper reviews the various improvements in oxygen usage that have been evolved over time to make oxygen a versatile tool to significantly reduce coke rate, increase melt rate, reduce raw materials costs, recycle environmentally hazardous wastes, inject ferro-alloys and carbon-bearing materials, and reduce emissions. Techniques used include tuyere injection with or without supersonic speed, and oxy-fuel burners with or without dust or ferroalloy injections through tuyeres. Also discussed in the paper are the differences between diffuser enrichment of wind and direct tuyere injection, subsonic vs. supersonic tuyere injection, oxy-fuel burner with and without solid injection, and several aspects of selecting an appropriate oxygen supply system.

Introduction

Enriching the cupola blast with oxygen has been in practice since early 1930s¹, but its widespread use started only in 1970s when oxygen cost started decreasing while coke and pig iron costs started escalating. Improvements in air separation technology with more energy efficient plant designs as well as development of on-site non-cryogenic generators have made the use of oxygen more cost effective. Today, oxygen use is economical for most cupola operations.

An increase in melt rate and/or reduction in charge material cost are the prime driving forces to use oxygen in cupolas. Cupola production can be increased either for intermittent or permanent requirements with oxygen enrichment often at a lower cost per ton of iron than with other alternative methods. Oxygen can also be used as a cost saving tool by allowing decreases in charged coke, partially substituting lower cost anthracite for more expensive foundry coke, replacing pig iron with less expensive charge metallics, and decreasing ferroalloy requirements.

The ability to instantaneously vary oxygen usage levels also provides the cupola operator with an extremely flexible tool to better control cupola operations in spite of occasionally unforeseen changes in coke and metallic charge quality, blast humidity and temperature, and cast house demand pattern. Today, hundreds of foundries worldwide use oxygen to make cupolas more productive and cost-competitive.

Oxygen enrichment is defined as a method of increasing the oxygen content of the blast air from 21% to a higher level. This is normally achieved by adding pure oxygen to the air whereby reducing the nitrogen content of the air-oxygen mixture. When the oxygen content is increased to, say, 23%, the oxygen enrichment level is $(23\% - 21\%)$ or 2.0%. Obviously, by increasing the oxygen content by 2%, the nitrogen content is simultaneously reduced from 79% (in atmospheric air) to 77% (in enriched air). Generally, the enrichment levels practiced in cupolas range from 1% to 5%. Higher levels of 8-9% enrichment are sometimes practiced in specific cases in large cupolas. Whether oxygen is mixed with air or directly injected into a cupola, traditionally oxygen intensity is referred by the enrichment level. In case of direct injection it simply means how much the enrichment level would have been had the directly injected oxygen been mixed with air.

Diffuser Enrichment

Most of the oxygen-enriched cupolas worldwide use diffuser enrichment of the blast. This method is the simplest and least expensive method to oxygen-enrich a cupola. It requires almost no maintenance of the oxygen system. Gaseous oxygen is introduced into the wind main through a diffuser and mixed with the blast air before the enriched blast enters the tuyeres (Figure 1). The result is a uniform distribution of well-mixed oxygenated air to all tuyeres. However, in a divided blast cupola, only the bottom row of tuyeres supply the oxygen enriched air. An undesirable secondary melt zone could develop if the oxygen-enriched air is supplied through the top row of tuyeres also.

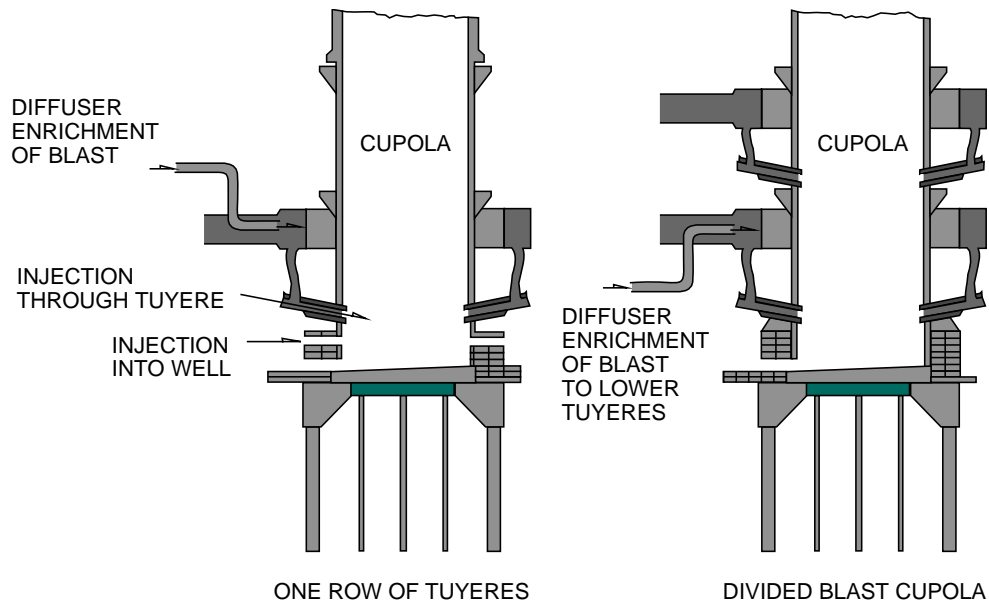


Figure 1: Methods of introducing oxygen into cupola

Estimating Productivity Improvements with Oxygen Enrichment

A theoretical studyⁱⁱ of the cupola melting process in 1930s established the following relationship for an oxygen enriched cold-blast cupola:

$$\text{Melt Rate (metric tonne/hr)} = \frac{60}{10} * \frac{W}{\frac{K * k}{100} (4.45) \left(\frac{100 + \eta}{100} \right)} * \frac{O_2'}{21}$$

Where,

W = Blast rate, Nm³/minute

K = Coke consumption, kg/100 kg iron

k = Per cent carbon in the coke times 100

η = Combustion efficiency, $\frac{CO_2}{CO + CO_2} * 100$

O₂' = Oxygen content of the cupola blast with or without oxygen enrichment

Simplifying the above relationship and converting to U.S. units,

$$\text{Melt Rate (short ton/hr)} = 7948 * \frac{\dot{Q}}{C * k * (100 + \eta)} * \frac{O_2'}{21}$$

Where

\dot{Q} = Cupola blast rate, standard cubic feet per minute

C = Coke consumption, pounds of coke per short ton of iron

The above relationships show that the melt rate will be increased by at least a ratio of $\frac{O_2'}{21}$ minus 1. This prediction only serves as first approximation. For example, if the melt rate with atmospheric air is set equal to 1, then the melt rate with 23% oxygen (2% enrichment) will at least be (23/21) or 1.10 times or a 10% increase. For 4% enrichment (i.e. 25% oxygen in the blast), the predicted melt rate increase is at least 19%. The actual increase can be even higher as factors like coke rate (K or C) reduction and decreased combustion ratio (η) with oxygen enrichment have not been included in the above ratio. In practice, at constant blast rate, each per cent of oxygen enrichment increases melt rate by 6-8%.

Equivalent vs. Supplemental Enrichment

In equivalent enrichment, total moles of oxygen introduced into the cupola remain unchanged. This is achieved by reducing the original blast rate and then adding pure oxygen to make up the oxygen moles lost due to reduced blast volume. This is typically done when no melt rate increase is desired. However, in case of melt rate increases, the existing blast rate is unchanged and additional moles of oxygen are added to the wind main.'

Benefits of Diffuser Oxygen Enrichment

The benefits of oxygen enrichment vary depending on how oxygen is used - whether it is for raw materials savings or melt rate increases or operational flexibility. Table 1 includes the benefits of oxygen enrichment that have been realized in a wide range of foundriesⁱⁱⁱ.

TABLE 1
Benefits of Oxygen Enrichment

	<u>Modes of Applications</u>		
	<u>Raw Material Savings</u>	<u>Production Increase</u>	<u>Greater Cupola Control</u>
Tap Temperature Increase	50 - 200°F	50 - 100°F	50 - 200°F
Increased Production	Intermittent	10 - 25%	Intermittent
Coke Savings	4 - 15%	0 - 5%	None
FeSi Savings	5 - 20%	0 - 5%	None
Pig Iron Substitution	5 - 50%	0 - 10%	None
Use of Lower Grade Raw Materials	Yes	Yes	No
Holding Furnace Fuel Savings	20 - 50%	0 - 50%	None
More Fluid Slag	Yes	Yes	Yes
Fluorspar Savings	30 - 100%	0 - 100%	None
Limestone Savings	0 - 10%	0 - 10%	None
Eliminate Bridging & Channeling	Yes	Yes	Yes
Refractory Patch Material Savings	0 - 10%	0 - 10%	None
Preheater Natural Gas Savings	10 - 15%	None	None
Hot Blast Temperature Substitute	Yes	Yes	Yes
Reduced Stack Gas Volume	Yes	None	None
Reduce Pigging	50 - 100%	50 - 100%	50 - 100%
Reduce Cold Metal Misruns	50 - 100%	50 - 100%	50 - 100%
Reduce Time to First Tap Metal	25%	50%	50%

Tuyere Injection

Since the blast velocity near the cupola center is much lower than near the shell, an uneven distribution of gas flow occurs. This results in variations in CO₂ content of the ascending gas stream, which affects the melting and thermal efficiencies of a cupola. As the tuyere velocity content of the furnace atmosphere in order to maintain the final carbon concentration at the surface of the part, at a specified value. Important process variables include furnace temperature, furnace atmosphere composition, carburizing time and the carbon potential of the atmosphere. In order for carburizing to occur, the carbon potential of the atmosphere must be greater than the carbon potential of the component's surface. How much greater will affect the rate of carburizing.

Maximum tuyere blast velocity is limited by the formation of raceways in front of the tuyere nose. As the blast velocity increases beyond 90-120 meter/sec (300-400 ft/sec) in a cold blast cupola, the net combustion reactions at the tuyere area produce nearly pure CO, resulting in a sharp decrease in heat release to 500 kcal/kg (4350 Btu/lb) of carbon and in flame temperature to 1350° C (2460° F)^{iv}. Although high CO gas is desirable in reduction smelting of blast furnace, it is less efficient in high temperature iron melting in a cupola. Hence, caution should be exercised while designing tuyere injectors to restrict excessively high oxygen velocity.

Tuyere injection involves adding pure oxygen directly to each individual tuyere (or every other tuyere) by means of stainless steel or monel injector tubes (Figures 1 and 2). In addition to a shutoff valve, each injector should have a manual ball valve so that the oxygen level can either be balanced or differentiated around the cupola combustion zone as conditions warrant.

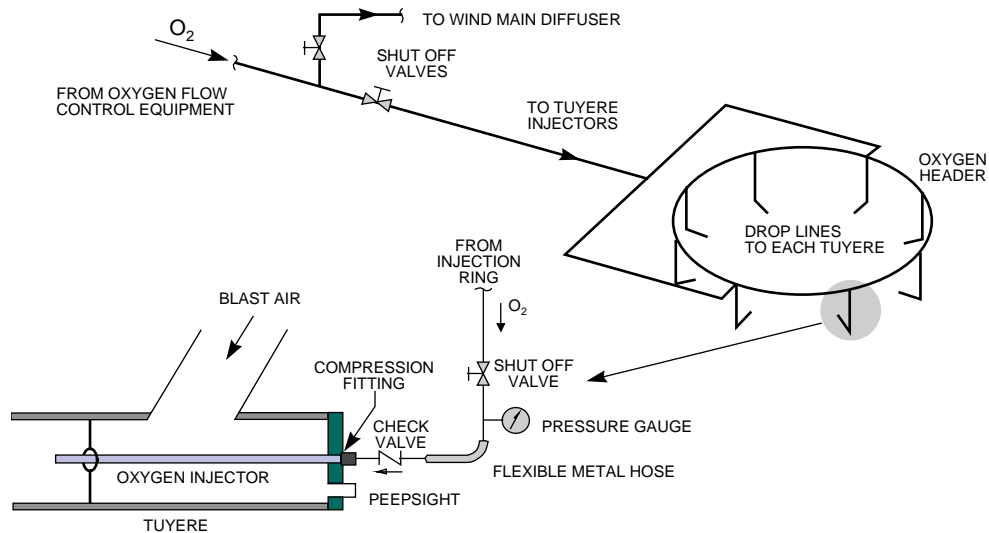


Figure 2: Method of oxygen enrichment by tuyere injection

Because tuyere injectors are not in direct contact with molten iron they are less likely to experience the problems of slag and metal attack, normally associated with well injection. As opposed to diffuser enrichment, tuyere injectors need periodic checking and replacement since the injectors are exposed to high temperatures, resulting from radiative heat transfer which can cause injection lances to warp and sag. Tuyere injection, when designed and operated at the proper flow rates and velocities, is more effective than diffuser enrichment. The choice between sub-sonic and super-sonic injection depends primarily upon the operating characteristics of a particular cupola and the complexity a foundry plans to undertake. Generally, supersonic injection can be more effective in cupolas with low blast velocities or of larger diameter.

An important economic benefit of tuyere injection is that it allows the cupola operator to avoid oxygen loss normally associated with diffuser enrichment due to blast leakage normally found in the wind main. Figure 3 illustrates this. A 15% blast leakage rate after the diffuser means 15% less oxygen volume going into the cupola with diffuser enrichment compared to tuyere injection at an equivalent oxygen use rate. In other words, the same level of enrichment can be achieved in this example through tuyere injection with 15% less oxygen consumption compared with diffuser enrichment. This is a significant savings in oxygen cost.

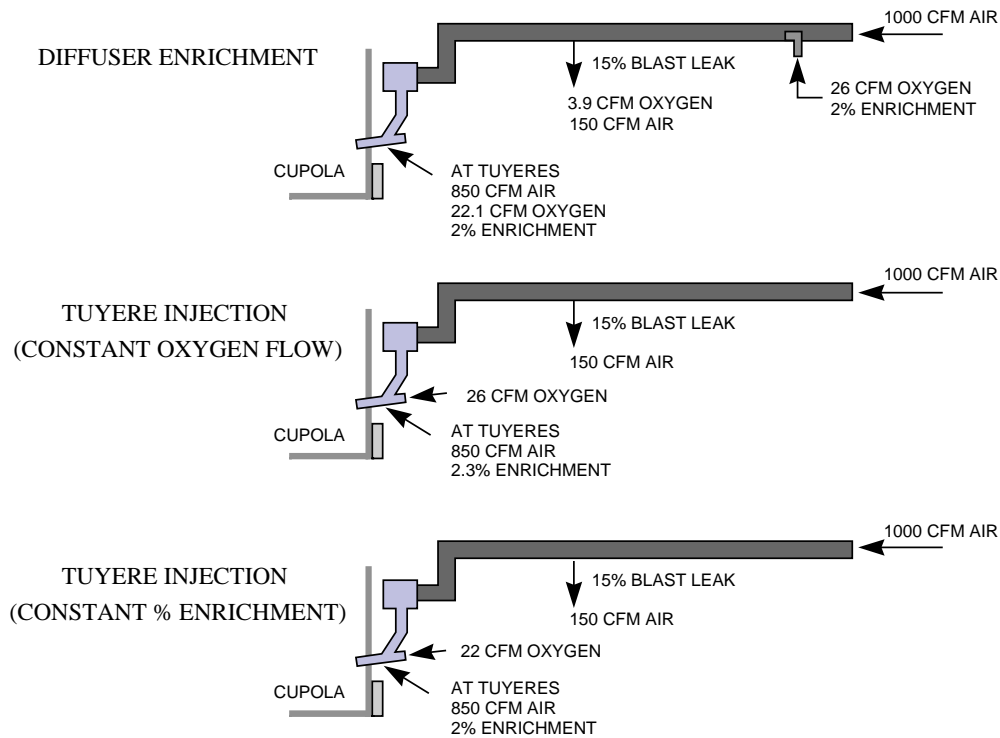


Figure 3: Eliminating oxygen loss from blast leaks

Table 2 shows the typical benefits available from tuyere injection and compares the ranges with those from diffuser enrichment of 2 to 4% at a wide range of cupola sizes. The increased benefits of tuyere injection compared with those of diffuser enrichment are the result of several factors including eliminating the influence of blast leakage, achieving greater penetration and better mixing of combustion gases and uniformity of temperature profile of gases, higher oxygen partial pressure in the combustion zone leading to a higher temperature, etc. Not all benefits at the highest levels can be concurrently obtained in either diffuser or tuyere injection.

TABLE 2
Diffuser versus Tuyere Injection

Oxygen Application	<u>Benefits</u>	
	Diffuser Enrichment	Tuyere Injection
Coke Savings	4 - 15%	8 - 20%
FeSi Savings	5 - 20%	10 - 25%
Melt Rate Increase	10 - 25%	30+%
Spout Temp. Increase	14 - 42° C (25 - 75°F)	28 - 56° C (50 - 100°F)
Hot Blast Fuel Savings	11 - 20%	11 - 20+%

Tuyere Injector

Two types of tuyere injection - subsonic and supersonic - are currently practiced. The exit velocity of oxygen from the tip of the injector or nozzle determines whether it is sub-sonic or super-sonic injection. The sonic (sound) velocity of oxygen in air is 327 m/sec (1074 feet per second). Higher velocities may provide better penetration of oxygen molecules into the coke bed. Higher velocities insure the oxygen jet remain stable for longer distances, without allowing the jet diluted with the surrounding blast. This results in a jet of pure oxygen to produce a locally concentrated combustion zone with a corresponding higher combustion temperature and higher heat intensity.

Most tuyere injectors are sized so that optimum operating pressures range from 3.5 to 10.5 bars (50 to 150 PSIG). Oxygen velocities through these injectors typically range between 200 and 650 m/sec (650 and 2150 ft/sec). The inside diameter of these injectors usually ranges between 3 and 20 mm (1/8 and 3/4 inch), depending on average blast rate and desired enrichment level, the combination of which determines the oxygen flow rate. Based on required oxygen flow rate and operating pressure, the injector size is designed to maintain a predetermined oxygen velocity. The injectors should be inset about 7.5-15.0 cm (3-6 inches) from the end (nose) of the tuyeres. The recommended operating pressure for supersonic nozzles is 7-10.5 bars (100-150 PSIG). For smaller cupolas, supersonic tuyere injection may neither be needed nor practical.

To eliminate a potential central "dead zone" in cupolas of 1.5 m (60 inches) or more in diameter, special tuyere injectors with Laval (convergent-divergent) nozzles, which provide an oxygen exit velocity of Mach 2-3, are preferred^v. Typical tuyere (blast) velocity cannot completely eliminate this dead zone, which is typically located at the center of a big cupola near the lower part of the shaft. Supersonic oxygen injection could supplement higher tuyere velocity to minimize the effects of the dead zone.

When oxygen needs to be delivered within a desired range of velocity and pressure, the design of the nozzle plays a critical role. In general, three basic designs are employed: straight bore tube, converging nozzle, and converging-diverging nozzle.

Straight Bore Tube: This is the simplest design and is inexpensive, but is likely to experience more wear and/or damage. It is easy to fabricate, requires frequent replacements, and the oxygen flow characteristics do not change as the tube shortens during use. The maximum velocity that a gas (oxygen) can attain in a straight bore tube is sonic (the speed of sound, commonly called Mach 1 which is approximately 327 m/sec or 1074 ft/sec in air at standard conditions). Upon exiting the tube, the gas at Mach 1 will attain supersonic velocities if it exits at a pressure greater than the ambient pressure. This is commonly referred to as an under expanded jet. This under expanded jet expands rapidly and dissipates in velocity relatively close to the nozzle exit (Figure 4). Although it is technically possible to develop supersonic velocity with a straight bore tube, it rapidly loses its stability and integrity over a very short distance to make any significant effect. Straight bore tubes require relatively high pressures to develop under expanded jets.

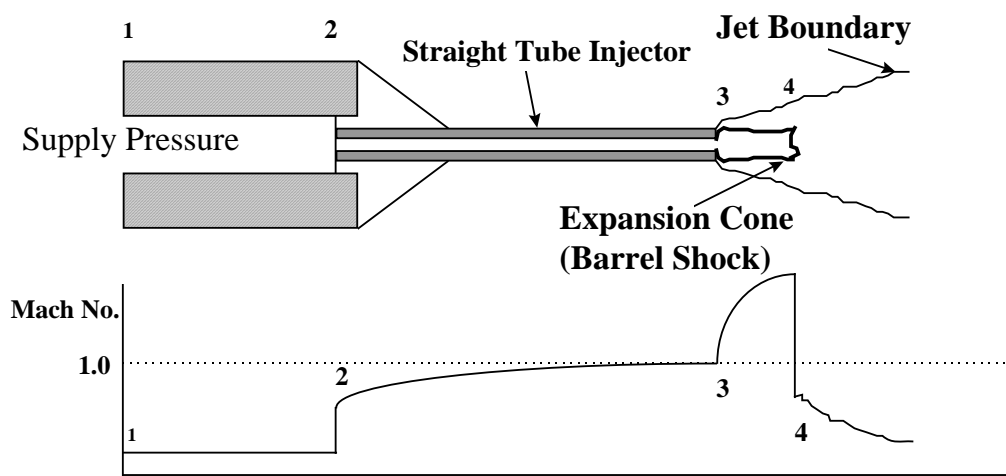


Figure 4: Gas Velocity Profile for a Straight Tube

Converging Nozzle: A converging nozzle is used to accelerate a subsonic flow to sonic velocity. Similar to the straight bore tube, a maximum velocity of Mach 1 can be attained at the nozzle exit. The converging nozzle requires a lower supply pressure than that for a straight tube due to lower frictional losses, but attains similar flow characteristics (under expanded jet) at the exit. This type of nozzle is rarely used in the cupolas.

Converging-Diverging Nozzle: By properly designing a diverging section downstream of a converging nozzle, it is possible to develop supersonic velocities. The diverging section allows the gas (oxygen) to expand in a controlled manner to develop exit velocities greater than Mach 1 in a fully expanded state (Figure 5). A converging-diverging (C-D) nozzle can be operated with no further expansion outside the nozzle. Hence, a C-D nozzle produces a gas stream that maintains its velocity at greater distances from the nozzle exit. This feature is beneficial if greater cupola penetration is required without diluting the pure oxygen stream with the blast air surrounding it.

Lance nozzles are designed for a specific oxygen flow rate to deliver supersonic exit velocity in order to achieve better penetration than is possible with an oxygen-enriched air blast. The oxygen accelerates in the converging section up to sonic velocity (Mach =1) in the throat area. The oxygen then expands in the divergent section. This expansion decreases the temperature, density, and pressure. At the same time, the velocity increases to supersonic velocity (Mach >1).

Decades ago it was found that higher air blast velocity in cupolas eliminate double melting zone and cold iron, reduce silicon loss, and improve coke rate. The results of high tuyere velocity and reported better performance of tuyere oxygen injection than diffuser enrichment, indicate that the depth of cupola penetration is important. This leads the cupola operators to prefer supersonic injection to straight bore tube injection or other methods of oxygen usage in cupolas.

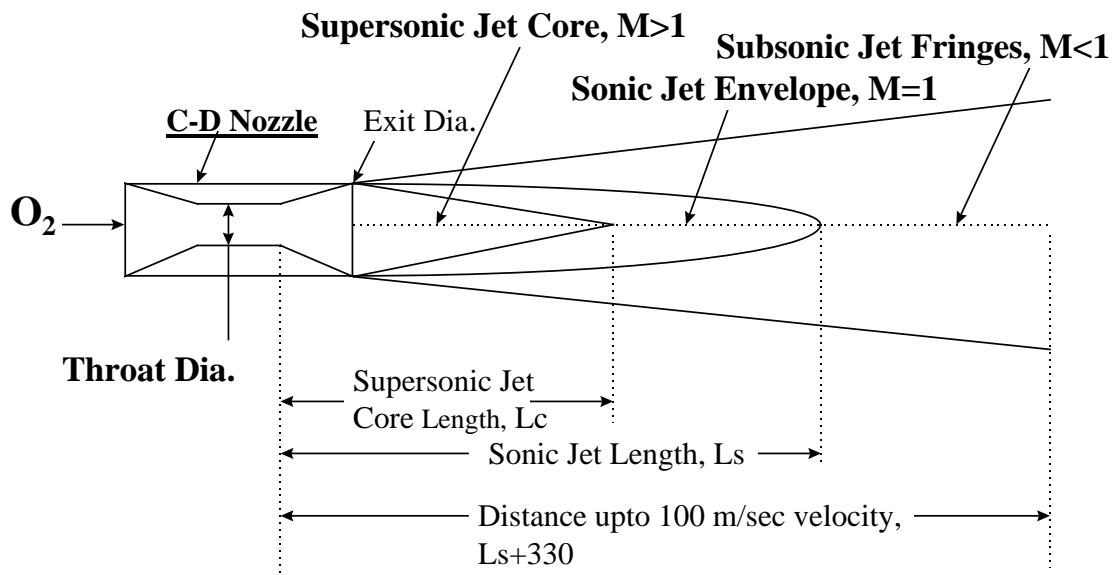


Figure 5: Structure of Supersonic Oxygen Jet

Influence of Pressure and Throat Diameter on Mach Number

Figure 6 shows as the oxygen pressure is increased, Mach number increases. But, the relationship between Mach number and throat diameter is inverse. Although these figures are based on an oxygen flow rate of 55 or 270 Nm³/hr (2000 or 10000 SCFH) per tuyere, exactly similar patterns are also obtained for any oxygen flow rates. These figures also show that for the given oxygen flow rate when the oxygen pressure is less than about 1 bar (15 PSIG), the oxygen exit velocity is less than Mach 1 i.e. sub-sonic. Hence, it is important to design the C-D nozzle in such a manner that for the available oxygen pressure, the exit velocity is greater than Mach 1. The throat diameter is one of the important design criteria.

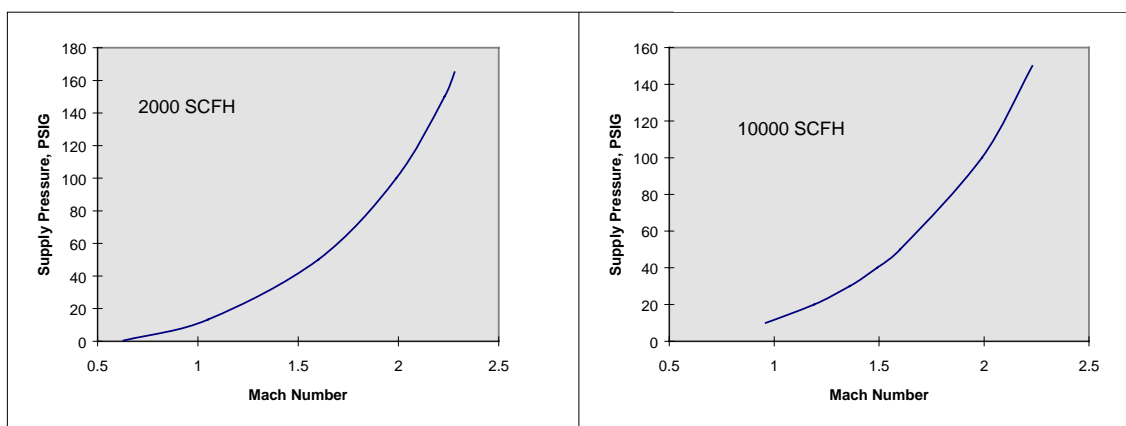


Figure 6: Pressure vs. Mach number for C-D Nozzle

Determining Thrust Created by Oxygen Jets

The momentum of the oxygen jet provides energy to penetrate into the coke bed to promote combustion over a small, concentrated area with 100% oxygen, undiluted with surrounding blast air. The jet velocity and penetration are functions of the oxygen injector design. The thrust created by an oxygen jet can be calculated by the following formula:

$$F = Q \cdot V_e / g$$

where,

F = Thrust or force

Q = Oxygen flow rate in mass

V_e = Oxygen exit velocity

g = Acceleration due to gravity

By adjusting the supply pressure, one can have an oxygen jet of subsonic (Mach 0.96 at 0.7 bar or 10 PSIG) or supersonic (Mach 2.23 at 10.3 bars or 150 PSIG) type (Figure 6) with a C-D nozzle of appropriate nozzle dimensions. According to the above relation, the thrust (force) of the jet changes as the velocity (Mach number) changes which is dependent on supply pressure.

Higher force allows better integrity and stability of the oxygen jet as it travels. Force of an oxygen jet will have a different influence on a close packed coke bed than on a liquid metal bath. The jet force creates a depth of penetration in molten bath and forms a cavity profile. In a solid coke bed, it merely ensures a stable, pure oxygen jet reacting with hot coke, generating higher temperatures than would be possible with diluted oxygen-enriched air stream. As this reaction is more intense and the momentum of the jet has certain force, the reaction front moves forward and towards the cupola center.

Effect of Mach Number on the Oxygen Jet Length

Generation of long and penetrating jet is of paramount interest in numerous metallurgical applications. To be cost-effective, optimization of flow rates and supply pressures is needed to maximize benefits of oxygen jets. In a study^{vi}, oxygen jet lengths at various flow rates and pressures were estimated. This is important before installing a high-pressure oxygen system (costlier) to generate a higher mach number jet than is necessary. Figures 7 and 8 show the impact of Mach number and oxygen inlet pressure on the oxygen jet lengths. The curves represent supersonic jet core length (L_c), sonic jet length (L_s) and distance (L_{sX330}) at which axial oxygen-velocity drops to 100 m/sec (330 ft/sec) for two different flow rates, 235 Nm³/hr (9000 SCFH) and 470 Nm³/hr (18000 SCFH).

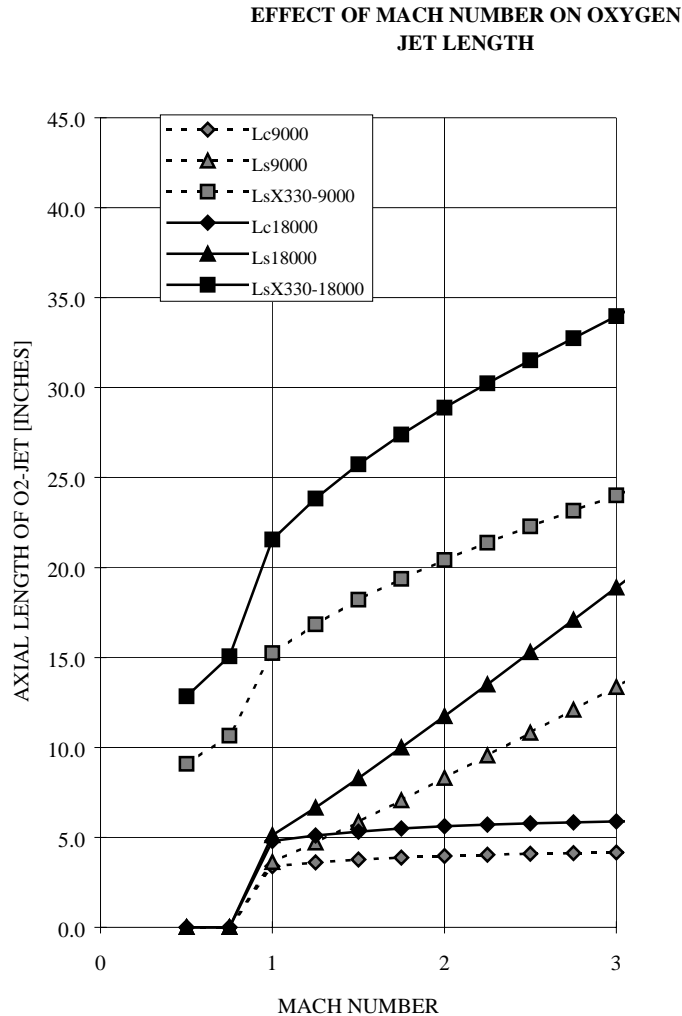


Figure 7: Effect of Mach Number on Oxygen Jet Length

The axial length of a supersonic jet core (Figures 5 and 7) sharply increases until it reaches Mach 1 and then it tapers off. However, the sonic envelope continues to expand as Mach number increases. Since the coke bed is close to the tuyeres, it might be adequate to have a Mach number around 2 before the raceway becomes an issue.

As mach number and inlet pressure are directly correlated, the influence of pressure on axial length of a jet (Figure 8) is similar to that of Mach Number. Also, no significant impact of pressure beyond 7-10.5 bars (100-150 PSIG) range is envisioned.

15% less oxygen volume going into the cupola with diffuser enrichment compared to tuyere injection at an equivalent oxygen use rate. In other words, the same level of enrichment can be achieved in this example through tuyere injection with 15% less oxygen consumption compared with diffuser enrichment. This is a significant savings in oxygen cost.

Hot Blast and Oxygen Enrichment

While oxygen is used on a continuous basis in cold blast and divided blast (only though the lower row of tuyeres) cupolas for substantial raw materials cost savings and/or productivity improvements, the incremental benefits of oxygen in hot blast cupolas are worth mentioning. Tables 3 and 4 include results from several case studies some of which were reported in various literature.

Table 3

Cupola ID	Blast, Nm ³ /hr	Base Case/ Oxygen	Results	
2.8 m	47 580 @ 482°C	2% Diffuser Enrichment	13.6% coke charge	58 TPH
	47 580 @ 482°C	5.7% Tuyere Injection	10.9% coke charge	71 TPH
1.8 m	13 600 @ 481°C	Base Case, no oxygen	Base	10 TPH
	12 000 @ 481°C	2% continuous, diffuser	14.5% coke savings	10TPH
1.8 m	16 860 @ 316oC	Base Case, no oxygen	Base	25 TPH
	15 120 @ 316oC	2% continuous, diffuser	6.8 kg coke, 9.1 kg Fesi savings/tonne	25 TPH
2.2 m	Blast n.a.@ 316oC	Base, no oxygen		28 TPH
		2% continuous, diffuser		33.6 TPH
1.4 m	9 360 hot blast	Base, no oxygen	20% coke, 2.5% FeSi	10 TPH
	9 360 hot blast	2% enrichment	18% coke, 1.5% FeSi	10TPH
2.2 m	21 600 hot blast	Base case, no oxygen	11.5% coke	25.4 TPH
	21 600 hot blast	3% enrichment	12.0% coke, Tap 65oC↑	30.5 TPH

In an early 1980s study in Japan^{vii}, the following performance data emerged:

Table 4

	Cold Blast	Hot Blast	Oxygen Enrichment	Hot Blast + Oxygen Enrichment
Blast Rate, Nm ³ /hr	1500	1380	1260	1200
Blast Temp., °C	Cold	350	cold	350
O ₂ in blast	21	21	25	25
Coke Bed height, mm	1100	900	900	900
Coke Rate, %	14.0	11.5	11.5	10.5
Thermal Efficiency, %	31.0	37.9	36.7	42.1
Pig Iron in charge, %	55	n.a	50	45
Melt Rate, metric T/hr	1.80	n.a	2.37	2.54

Hence, oxygen can improve the melting thermal efficiency of a hot blast cupola with resultant benefits of increasing the metal to coke ratio and the cupola productivity beyond the limits of hot blast capabilities.

Oxy- Fuel Burner

In 1966, burners were developed to sustain an oxy-fuel flame within existing tuyeres of cupolas^{viii}. They were experimentally used in seven out of eight water-cooled tuyeres of a 2286 mm (90 in.), 649°C (1200°F) hot blast acid-lined, water wall cupola. Use of burners promoted carbon pick up, enhanced charge silica reduction to silicon, and yielded savings in coke consumption. Although no increase in metal temperature above normal was observed, temperature recovery after spills and wind changes was vastly improved, which could be used as a valuable control tool. But burners seem to have the greatest application where additional production would be required from existing facilities.

Water-cooled oxy-natural gas burners produce an estimated 25% increase in melt rate. However, a melt rate increase of as much as 90% with oxy-oil burners firing at a rate amounting to one-half of the total energy supplied by charge coke has been reported^{vii}. The lower melt rate increase with natural gas might be the result of lower available C/H ratio in natural gas (3.08) compared with that of fuel oil (6.98 for #2 oil). For unit weight of fuel, natural gas produces 1.81 times (by weight) the amount of H₂O that is produced by #2 oil^{ix}. The water vapor formed as a result of the higher hydrogen content of natural gas lowers the cupola temperature due to the endothermic water-gas reaction. The most satisfactory results were obtained when natural gas was fired with 75% of the stoichiometric oxygen, and fuel oil was fired with 60 to 100% of the stoichiometric oxygen, 100% being more economical. Straight oil injection without oxygen resulted in a drastic chilling of the cupola with subsequent loss of carbon and silicon. Oxygen requirement at maximum production rates varied from 28 to 40 m³ (1000 to 1430 scf) per ton of iron.

During the mid-1990s, the use of an oxy-fuel burner in a hot blast, 10-14 mt/hr (11-15 st/hr) cupola delivered the following benefits: iron temperature increase by up to 50°C (90°F), melt rate increase by about 30% while partially replacing foundry coke^x.

With the burner, the melt zone of cupola can be moved and stabilized in a way to improve cupola operation. Refractory wear can be minimized and more evenly distributed over the entire wall perimeter. When supplemental energy is provided by the burners, the iron temperature is increased according to the amount of energy introduced. It is assumed that about 1.7 to 2.5 kWh per tonne (1.5 to 2.3 kWh per ton) of liquid iron is required to increase the temperature by 1°C (1.8°F). As the temperature of the iron is increased by 30 to 50°C (54 to 90°F) at an energy consumption of 360 to 1120 kW using an oxy-fuel burner in a 9.1-12.7 mt/hr (10-14 TPH) cupola, it can be concluded that about half of the energy provided by the coke is required from natural gas to achieve the same result.

The oxy-fuel burner can be used to improve the poor superheating efficiency of a cupola. When superheating of the iron is not required, the coke rate can be reduced. The iron at lower temperatures will find an equilibrium condition at higher melt rates when the blast rate is kept constant (Figure 9). Lower combustion efficiency (η_v) will also result in higher melt rates.

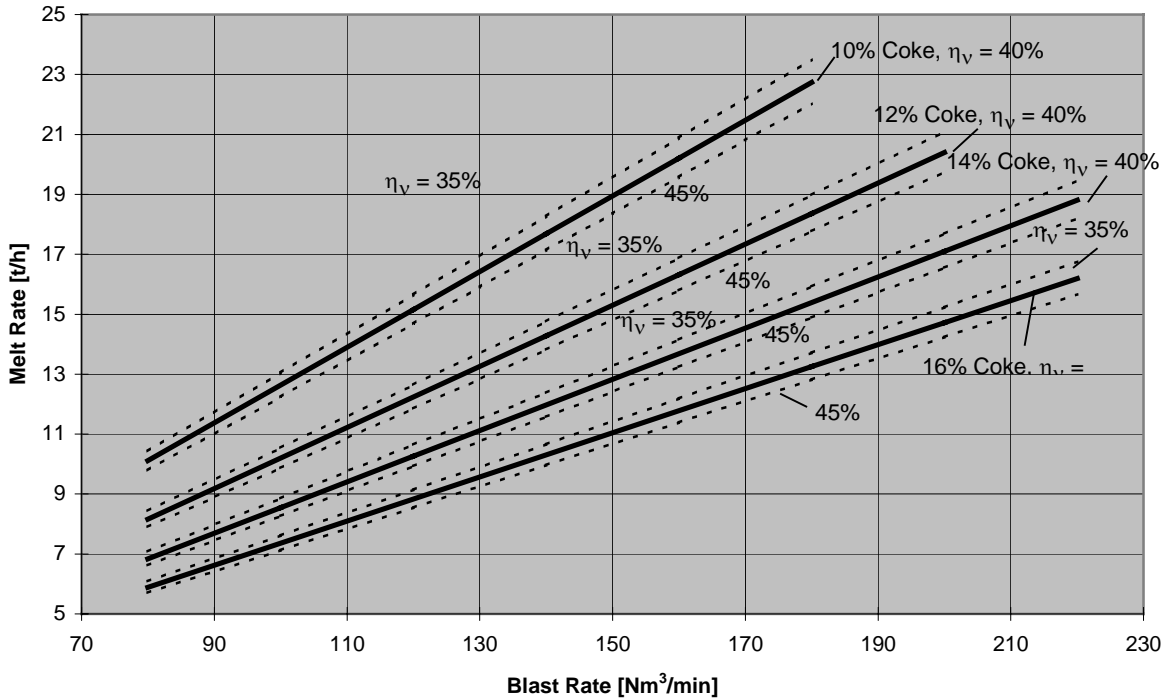


Figure 9: Interrelationship of blast rate, coke rate and melt rate.

Definition of combustion efficiency for the combustion of coke and hydrocarbons in a cupola:

$$\eta_v = \frac{CO_2 + H_2O}{CO + CO_2 + H_2 + H_2O}$$

where: CO_2, H_2O, CO, H_2 are the flue gas components in volume per cent.

Definition of coke rate: $Coke\ Rate = \frac{Coke\ Charge}{Metallic\ Charge}$

The desired melt rate can be adjusted by varying the blast rate. The oxy-fuel burner provides an additional tool to operate cupolas with more operating flexibility. The burners allow an introduction of 20% or more of the energy normally provided via the charged coke.

In Figure 10 the Jungbluth net diagram of the referenced cupola is shown. The lower net gives the base case data of the hot blast cupola. For coke rates of 10.5 and 12.8% and different blast rates, the operating points are displayed. The operating points while using the oxy-fuel burner can be seen in the upper net. The Jungbluth net diagram shows a shifting of operating conditions to higher melt rates and iron temperatures.

The burners can also be used without fuel (natural gas), in which case they act as direct tuyere oxygen injectors providing all the benefits of tuyere injection described earlier.

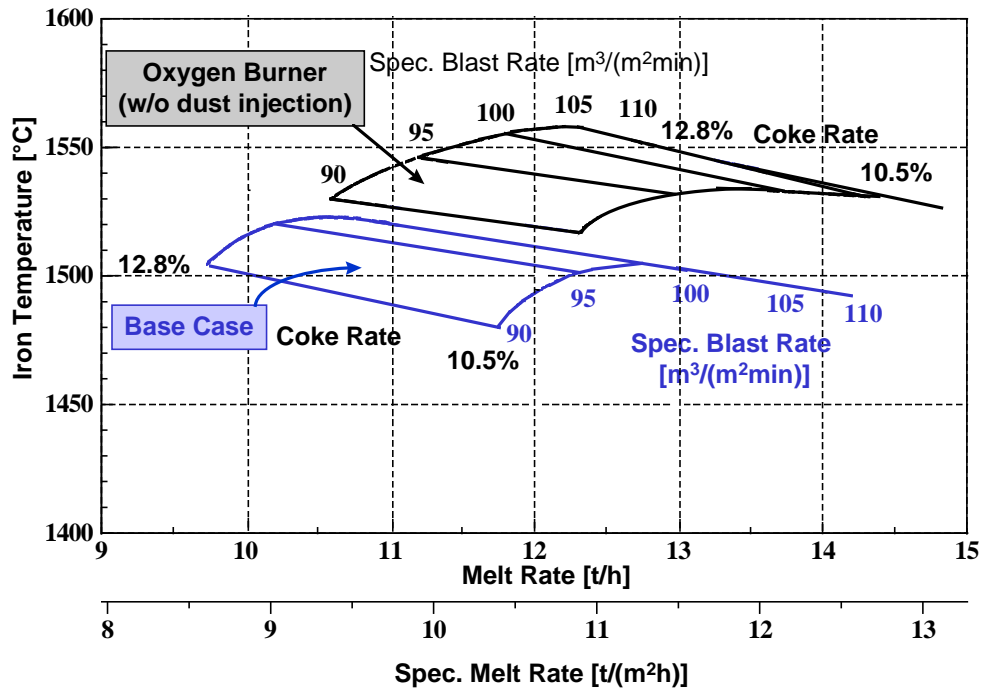


Figure 10: Jungbluth net diagram of the cupola with and without burner.

Heat balance of a 10-14 metric tonnes/hr (11-15.4 st/hr), hot blast (570°C or 1058°F) cupola with and without an oxy-fuel burner are shown in Figure 11 and 12. This comparison shows the reduction of energy input through coke with the burner operating.

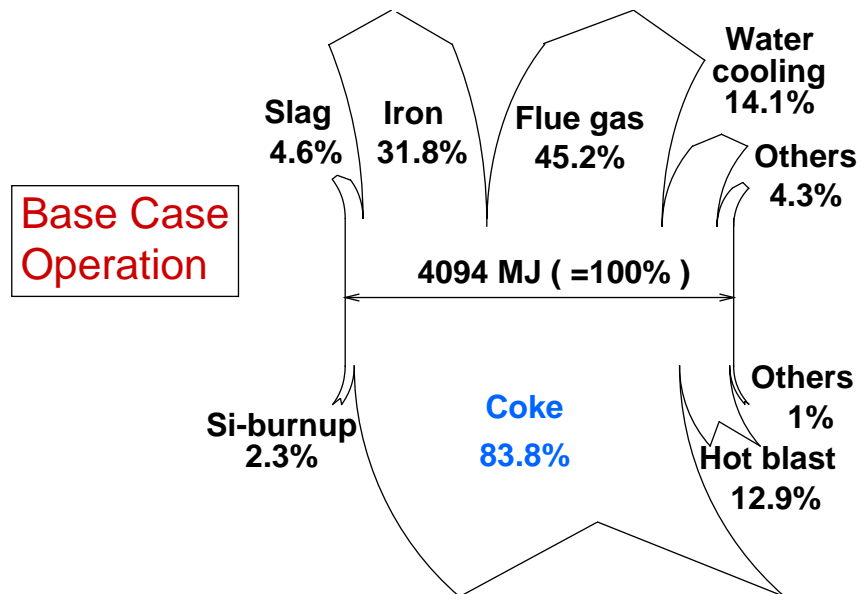


Figure 11: Base case - Cupola Heat Balance

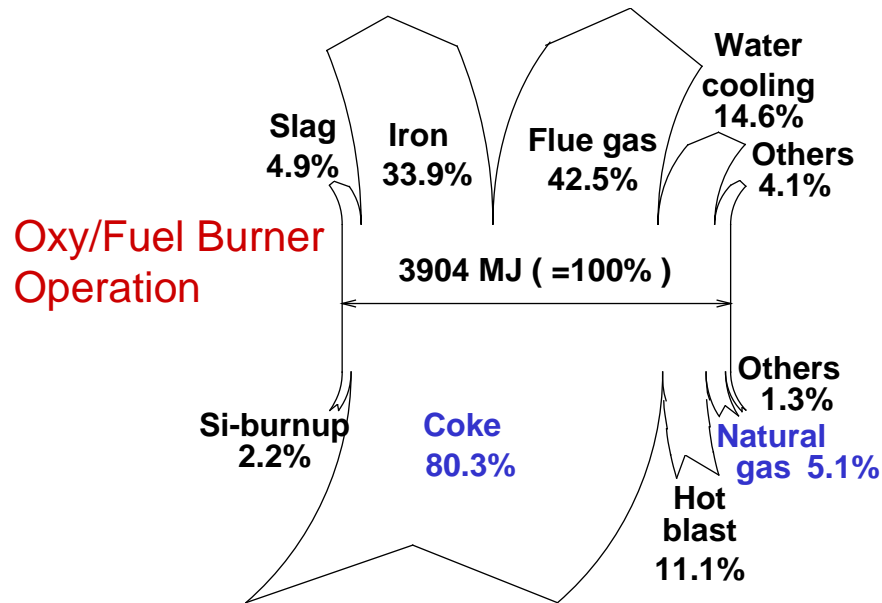


Figure 12: Cupola Heat Balance with Oxy-fuel Burner

Oxy-Fuel-Dust Injection System

At the 1994 GIFA exhibition, a new tuyere oxy-fuel system^{xi} for dust recycling was displayed. The system would allow disposal of particulate foundry wastes, such as filter dusts and resin impregnated sand. Dusts from sand preparation units and cupola off-gases can be converted to slag by blowing them into the cupola. Oxy-fuel burners are positioned in the tuyeres. Recyclable materials are injected through the burners into the cupola while supplemental energy is provided simultaneously also through the burner. This energy prevents freezing of the molten iron, which could result due to the cooling effect of injecting cold materials. When the injected waste is carbon-rich, a net fuel savings of 10% is attained. Most other components enter into the slag for low cost disposal. The zinc content of the recycled materials can be concentrated to a level where the material turns from a high-cost disposal waste item to an economic commodity. This dust injection system can also provide up to a 30% melting rate increase. With the ever-decreasing availability of dumping sites, the new process is of great importance to the foundry industry.

Oxy-fuel-dust Burner

To facilitate injection of flue dust into the cupola, the original coke breeze burner from the 80's has been modified and is now used as an effective cupola tuyere burner^x. A schematic of the oxy-fuel dust burner installation is shown in Figure 13.

The oxy-fuel burner is installed in a tuyere, and oxygen, natural gas and dusts or alloying agents are injected through this specially designed burner.

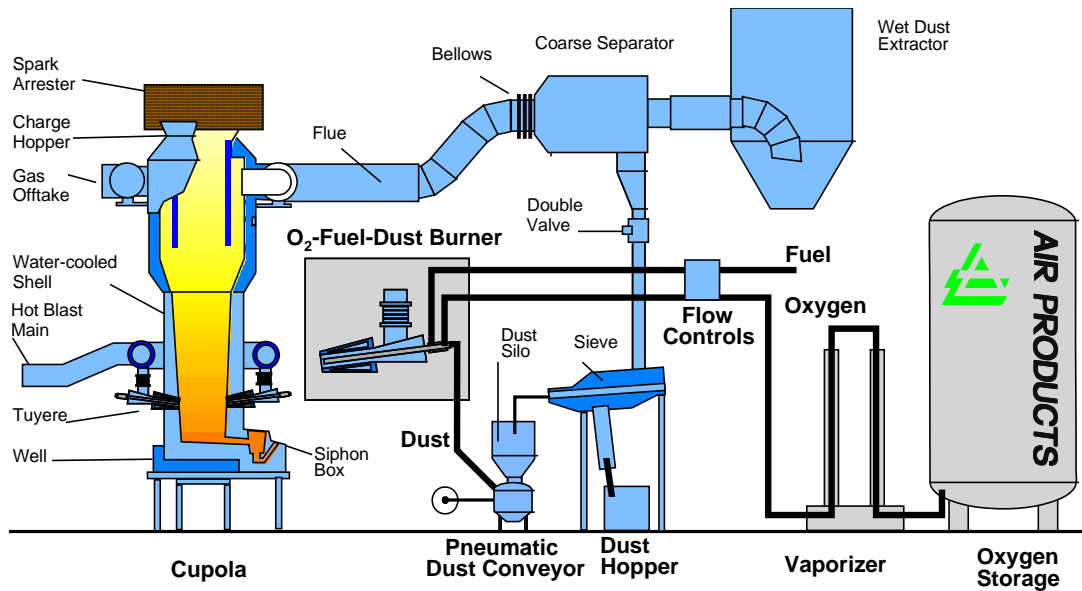


Figure 13: Schematic process for the cupola operating system.

The oxy-fuel-dust burner is of a compact design (Figure 14), so that it can be retrofitted into an existing tuyere without requiring major modifications. In addition, only an oxy-fuel burner can provide a very high temperatures flame (2700°C or 5000°F), which helps to melt and superheat the injected materials. The use of this burner prevents the injected cold materials from chilling the tuyere area.

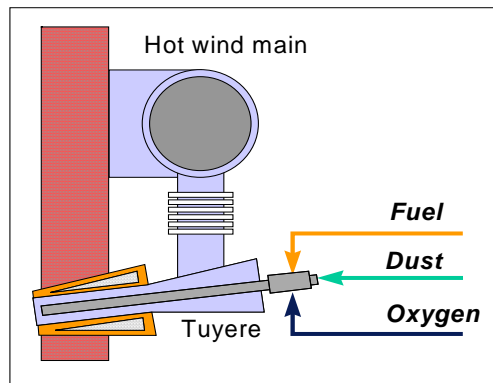


Figure 14: Oxy-fuel-dust burner

The burner flame is directed into the coke bed and away from the tuyere and water-cooling jacket to prevent overheating of the tuyere body. The gas temperature gradient in the cupola is equalized.

Dust Conveying System

A pneumatic blowing machine with a rotor is used to introduce solids into the cupola (Figure 13). Compressed air pushes the solid material through a hose to the oxy-fuel burner. The dust travels through the burner and is then equally distributed into the cupola.

With the oxy-fuel-dust injection system, not only re-injection of all generated dusts (typically, 4% of iron tonnage) into the cupola is possible, but also the injection of alloy materials and waste materials from other industries can be successfully processed.

Dust Types

In Table 5, typical compositions of the injected materials are given. Sweepings and finishing sand containing a high content of iron oxides can be reduced, and this increases metal yield. Cupola dust contains a large proportion of carbon, which adds energy to the process and improves cupola thermal efficiency. Iron oxide can be reduced and volatile heavy metals like zinc will be concentrated in the filter dust, converting a polluting waste into an economic by-product.

The following materials have been successfully injected into the cupola through the oxygen-natural gas burners with a pneumatic blowing machine:

- Cupola Dust
- Finishing Dust
- Sand Reclamation Dust
- Coke Breeze
- FeMn - Dust
- FeSi - Dust.

TABLE 5.
Compositions of injected waste materials (wt.%)

SWEEPINGS	CUPOLA DUST	RECLAMATION SAND DUST	FINISHING DUST
Fe ₂ O ₃ = 34.2	C = 28	SiO ₂ = 90	SiO ₂ = 48
SiO ₂ = 31.1	SiO ₂ = 25	Al ₂ O ₃ = 5	Fe _{tot} = 38
CaO = 9	FeO = 18	C = 3	Al ₂ O ₃ = 7
Al ₂ O ₃ = 8.2	CaO = 8	Others = 2	C = 2
SO ₃ = 4	ZnO = 5.6		Others = 5
ZnO = 3.1	Al ₂ O ₃ = 4		
MgO = 2.4	PbO = 0.4		
Others = 8	Others = 11		

It must be noted that, in combination with the burner technology, 80 to 100 kgs of dust per tonne (160 to 200 pounds of dust per ton) of molten iron can be injected. This is about four to five times the amount that can be injected without an oxy-fuel burner.

Oxy-fuel-dust Burner Results

In Figure 15 the interrelationship of blast rate, coke rate and metallic charge for different operating conditions is given. The bottom line represents the base case situation at a coke rate of 12.8%. The top line refers to the burner use without dust injection. As shown in Figure 15, the coke rate can be reduced to 10.6%, with a melt rate increase of 25-27%. When a dust mixture is injected along with oxygen-fuel burner firing, the coke rate is reduced from the base case of 12.8% to 10.8% with a simultaneous melt rate increase of 21 to 22%.

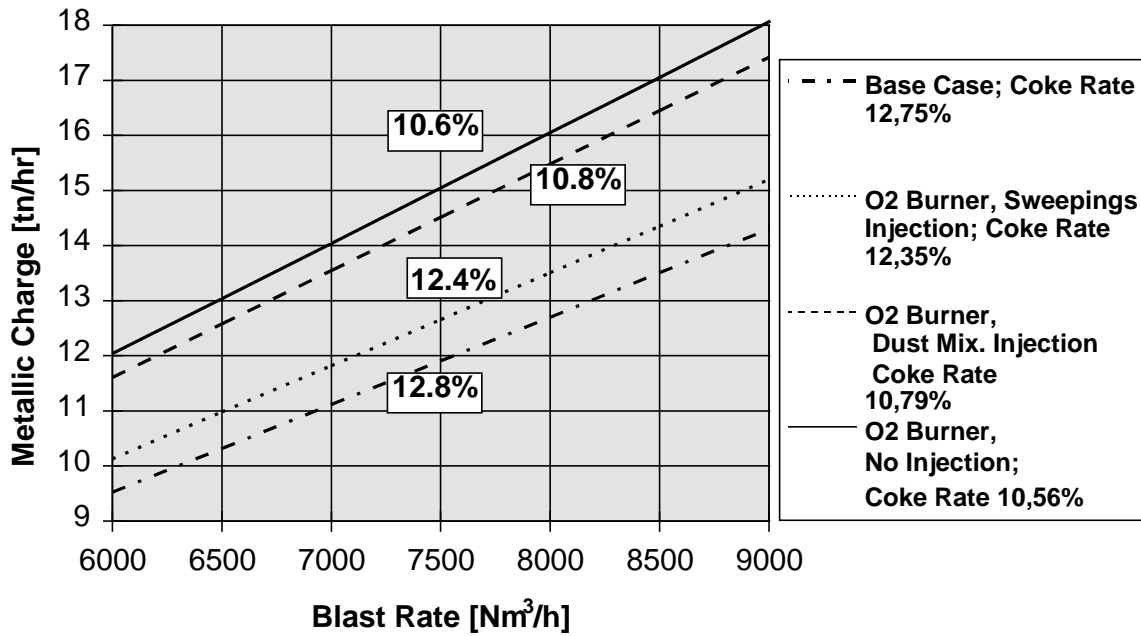


Figure 15: Oxy-Fuel-Dust Burner Results

This diagram reflects the findings that even during injection of materials, a melt rate increase was achieved. This can probably be explained by the fact that not only inert but also combustible components were injected with the dust. Hence, more energy per unit time was introduced with dust injection than without dust injection; the gas temperatures in the combustion and melting area were increased which, for the same coke rate, resulted in a higher CO content (Boudouard equilibrium) in the flue gas. In addition, the reduction of FeO and MnO, components of the injected materials, would consume carbon resulting in a slight increase of melt rate.

A mixture of several dust types (Table 5) enables a lower coke rate and, thus, an increase in the melt rate. The energy input through the oxygen-fuel burners can be adjusted. During the trial it was set to 3 to 6% of the total heat turnover per tonne of molten iron per hour.

Figure 16 shows the heat balance with dust injection through an oxy-fuel burner. This diagram is to be compared with the base case (Figure 11).

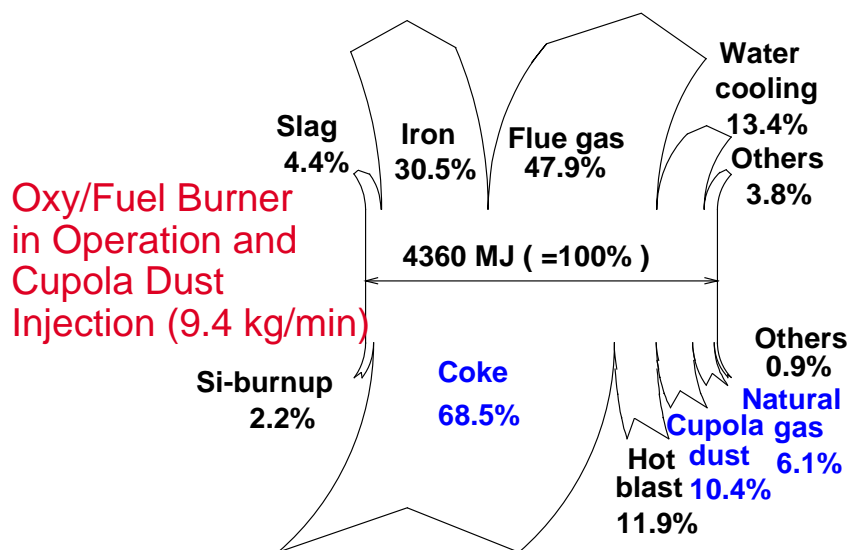


Figure 16: Heat Balance - Oxy-fuel-dust Burner-fitted Cupola

The following benefits^x have been realized at several oxy-fuel-dust installations:

- Increased melt rate by up to 30%
- Coke savings of 10-15%
- Increased spout temperature by 50°C (122° F)
- No chilling at the tuyere zone; tuyeres remain fully open
- Allows recycling of foundry wastes, reduces waste disposal costs and problems.

Energy Requirements

Oxygen enrichment increases the overall thermal efficiency of the cupola system by either providing increased productivity (melt rate) for a given amount of energy input or reducing energy consumption per unit of molten iron produced. A 1976 investigation^{xiii} on energy savings with oxygen enrichment of a cold blast cupola demonstrated that energy required to produce one ton of molten iron could be reduced by about 11% (including the energy required for producing, transporting and vaporizing oxygen) when 2% enrichment was used compared with no enrichment. The iron to coke ratio changed from 7.5:1 (no enrichment) to 9.2:1 (enrichment), an 18% coke savings with equivalent enrichment. The major contribution of oxygen in conserving energy in the cupola is the substantial reduction in coke requirements. When the total energy equivalent of coke including the energy utilized in its manufacture is balanced against the energy required to produce and deliver oxygen to the cupola, net energy savings up to 25% have been experienced. When equivalent enrichment is used to achieve coke reduction, as the enrichment level increases from 1% to 4%, the energy savings per ton of iron increases from 210-260 MJ (0.20 - 0.25 million BTU) to 790-1265 MJ (0.75 - 1.20 million BTU) that are equivalent to a specific energy savings of 4-5% to 15-24%.

A direct energy savings in the area of hot blast is realized when combustion air requirements are reduced. Typically, in a foundry employing 445 °C (830 °F) externally fired hot blast, the fuel consumed represents approximately 7.8% of the total energy required by melting operations. A 10 to 15% reduction in air demand reflects an approximate 1% reduction in overall energy usage. As a back up to a hot blast, oxygen can be used to maintain normal melting conditions with minimal effect on energy rate.

Total energy requirement per tonne of liquid iron at 1500 °C (2730 °F) in a cold blast cupola with only 30 to 32% energy utilization^{xiii} is 1209 kWh/t (4354 MJ/t). The specific enthalpy of a cast iron melt at 1500 °C is 387 kWh/t. If the coke consumption is reduced using hot blast or oxygen, the energy utilization increases to 42% with a corresponding energy requirement of 921 kWh/t (3316 MJ/t). This thermal efficiency increases to 60% in a coke less cupola with oxygen addition to the burners. This efficiency corresponds to 645 kWh/t (2322 MJ/t) energy requirement.

Effects of coke % increase, oxygen addition and blast preheat temperature on iron spout temperature have been estimated, as tabulated in Table 6:

TABLE 6

1% coke:	10-18 °C (18 – 32 °F) ↑
100° K blast preheat:	20 °C (36 °F) ↑
1% oxygen enrichment:	Hot blast : 6-14 °C (11-25 °F) ↑, Cold blast: 12-16 °C (22-29 °F) ↑
100° K blast preheat temperature is equivalent to 1.4% coke	
1 to 1.5% oxygen enrichment corresponds to 1% coke.	

Non-Cryogenic Oxygen Supplies

Barring a few exceptions, almost all cupolas are currently served by liquid oxygen supplies. On-site non-cryogenic oxygen generators are an alternative supply source and can offer great economic incentives in specific cases. Generally, large cupolas that operate essentially 6-7 days per week, over 20 hours per day are amenable to on-site generators. The option becomes more economical when high-pressure supplies are not needed, such as in diffuser enrichment. As the product (oxygen) pressure and purity become more critical, such as in supersonic tuyere injection or oxy-fuel burners, the cost of non-cryogenic oxygen supply increases. An on-site non-cryogenic oxygen generator will most likely require a backup liquid oxygen supply system. Non-cryogenic oxygen can provide 40-60% cost savings over the traditional liquid oxygen (LOX) supplies.

Vacuum Swing Adsorption (VSA) is a process used to selectively recover oxygen from air using a high-efficiency molecular sieve via non-cryogenic mode. A VSA unit generates oxygen on-site at the foundry. Figure 17 schematically shows a VSA oxygen generation process.

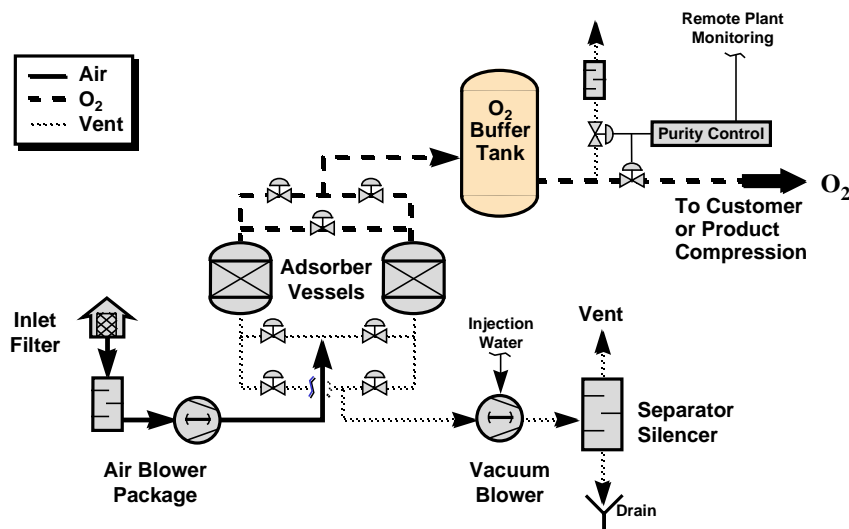


Figure 17: Vacuum swing adsorption oxygen production scheme

The oxygen VSA system can be turned down within the range of 90% to 50% of full production, providing a power savings of up to 35% with a steady-state turndown. These savings apply only to the VSA, and not to the oxygen compression power. The standard product pressure from the VSA unit is 0.2 bar (3 PSIG). Standard oxygen booster modules are added to meet higher product pressure requirements. However, this adds to the product cost (Figure 18).

The majority of cupolas do not operate around the clock, seven days a week. In a strong economy, a typical utilization range would be between 50% and 90%. This range can drop significantly to a range of 20% to 65% in a weak economy. This cyclical nature coupled with low utilization makes the on-site generator option an economically disadvantaged alternative. However, the purity is not critical as long as it is used for diffuser enrichment where higher pressure requirement is also not needed. Where high pressure (3.5+ bars or 50+ psig at use points) direct tuyere injection is employed, on-site generator needs a pressure booster on the tail end of the VSA unit. This requirement will dampen the economics. Typical non-cryogenically (adsorption) generated oxygen purity (90-93%) should not be a serious disadvantage when compared with cryogenically produced oxygen (99.995% purity). An oxygen purity of even lower than 90% is acceptable for cupola diffuser enrichment applications. Higher purity is typically preferred for tuyere injection and burner applications.

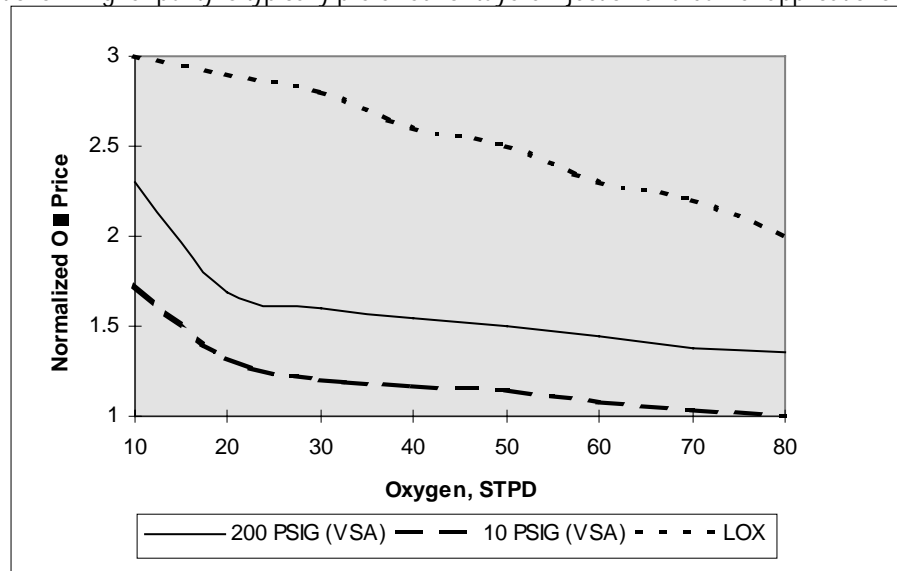


Figure 18: Effects of pressure and production method on oxygen price

Cupola operations, when they are at steady state melting conditions, require a consistent flow of oxygen, which can be met with an economically sized generator. But, during start up in the morning, higher levels of enrichment are often used. During this period and when the cupola operators need to adjust the melting operation to meet temporary demands for increased temperatures or above normal melt rates, the flexible nature of liquid oxygen supply becomes necessary to supplement otherwise economic on-site oxygen generator capacity.

Although a cupola operator can operate a cupola without enrichment for a period of time, it can cause detrimental effects on foundry production efficiency. A high performing, large foundry would need a back up supply of liquid oxygen either to supplement on-site generator capacity to meet period peak demands or an alternate source when the generator is shut down either for scheduled or unscheduled repairs.

Hence, purity, pressure, use pattern and back up needs are important criteria in selecting an appropriate oxygen supply option.

Summary

- Oxygen enhances cupola performance by
 - Diffuser enrichment of blast
 - Direct injection through tuyeres
 - Oxy-fuel burners
 - Oxy-fuel-dust burners
- Benefits of oxygen use in cupolas include melt rate increases, higher spout temperatures, lower raw materials costs, reductions in coke requirements, foundry waste recycling and operating flexibility.
- Supersonic oxygen injection is credited for better performance over straight tube tuyere injection; however, more in-depth controlled tests are needed to selectively quantify its impact.
- Future trend will include oxy-fuel burner use to significantly increase productivity and substantially reduce emission via partial substitution of natural gas (fuel) for coke.
- As environmental regulations become stricter, oxy-fuel-dust burner application will become a useful tool for prolonging the life of coke-based cupola operations.
- Selective foundries can take economic advantage by substituting on-site oxygen generators (VSA) for liquid supplies (LOX). However, these foundries must have high and steady use pattern of oxygen. Before switching from cryogenic (LOX) to non-cryogenic (VSA) oxygen specific site evaluation is needed. Factors to be evaluated include pressure, purity, and back-up (LOX) requirements as well as use pattern.
- As environmental pressure mounts across the globe, availability of coke will become more expensive and scarce. In contrast, technological advancements will allow the unit oxygen price cheaper on real terms. Hence, oxygen will play an even bigger role in iron melting in the next century.

References

- ⁱ F. Morawe, "Enriching the Blast of the Cupola Furnace with Oxygen," *Giesserei*, vol 74, pp 132- 155 (1930)
- ⁱⁱ Jungbluth, H. and Heller, P.A.: *Tech. Mitt. Krupp*, vol 1, pp 99-105, 1933
- ⁱⁱⁱ M.J. Stempo, "Determining the Economic Feasibility of Oxygen Enrichment of the Cupola Wind," *Cupola Operation - State of the Art* proceedings, AFS-CMI Conference June 1980, pp 205-222
- ^{iv} Rehder, J.E., "Tuyere Conditions in Cupolas," *Foundry M&T*, December 1982, pp 32-35
- ^v Franz Neumann , GuBeisen - Schmelztechnik, *Metallurgie, Schmelzbehandlung*, pp 34-43
- ^{vi} Z. Zurecki, *Internal Communications* at Air Products and Chemicals, Inc.
- ^{vii} Staff Writer, "High Efficiency Cupola," *Techno Japan* Vol. 19, No. 3, March 1986, pp 20-29
- ^{viii} J.W. Estes and B.G. Gary, "Oxy-Fuel Tuyere Burners," *Modern Castings*, June 1966, pp 111-118.
- ^{ix} *North American Combustion Handbook, Vol. 1*, Third Edition, pp 16-17, published by North American Manufacturing Co.
- ^x T.Niehoff, S. Smith, O. Frielingsdorf and D. Saha, "A Cupola Operating System for Dust Injection and Improved Process Flexibility," At the *102th AFS Foundry Congress* at Atlanta
- ^{xi} H.J. Heine, "Innovative Technologies Prominent at GIFA," *Foundry M&T*, August 1994, pp 34-36
- ^{xii} H.C. Rolseth, "The Effect of Oxygen Enrichment on Energy Consumption in Iron Cupola", *AFS Transactions*, vol. 84, Paper No. 76-42, pp 295-299 (1976)
- ^{xiii} Franz Neumann and Egbert Baake, "Reduction of energy consumption and environmental pollution during melting in iron foundries Part 1. Cupolas," *Casting Plant - Technology International* 3/1997, pp 18-27.

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