

CUPOLA AND COMBUSTION IN A CUPOLA

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The cupola is a vertical shaft type furnace having a cylindrical steel shell lined with refractive bricks and equipped with a wind box and tuyers for the admission of air. The charging opening is at the upper end of the furnace. The removal of molten metal and slag is at the lower end of the furnace. One of the outstanding features of the cupola is ascending flue gases pre heat the descending charges. The descending fuel replaces burned coke and maintains the original height.

The design and construction of the cupola has to be properly engineered to obtain the required efficiency. The figure 1 gives a sketch of a conventional cupola.

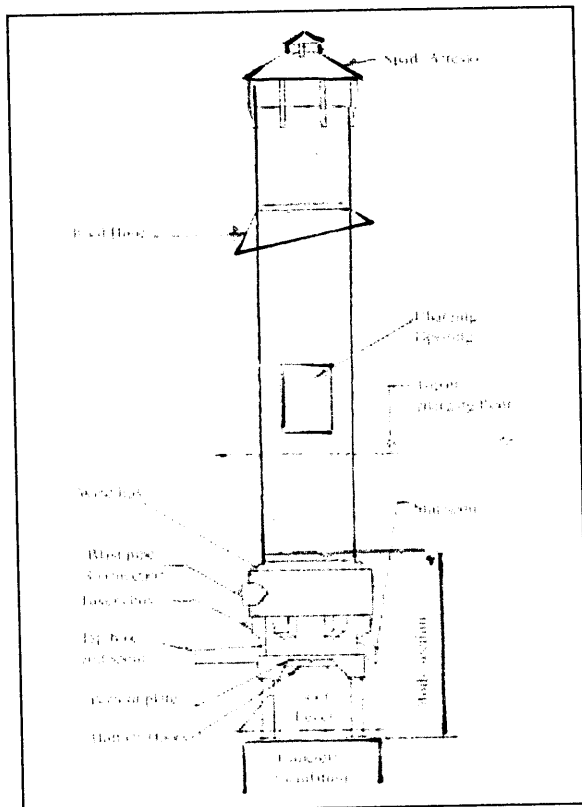


Fig. 1

In order for the combustion to occur intimate contact must be first made between carbon and oxygen. Once this is established the resultant CO_2 reaction proceeds. The speed of the reaction increases and becomes more and more dependent upon the physical factors. The condition surrounding the Co-reaction are governed with similar variables. The upper level of oxidation zone where the temperature is high the reaction proceeds first, very rapidly. The carbon and oxygen react each other in the cupola and conclude the basis of initial iron/coke/air ration.

- Increasing the air volume at a constant coke ratio results in lower Co: CO_2 reation, increase the melting rate but colder metal.
- Increase the amount of coke at a constant air volume result higher Co CO_2 ratio decrease melting rate but hotter metal.
- Decreasing the coke size at constant coke to the air ratio results in higher Co: CO_2 increase the melting rate but colder metal.

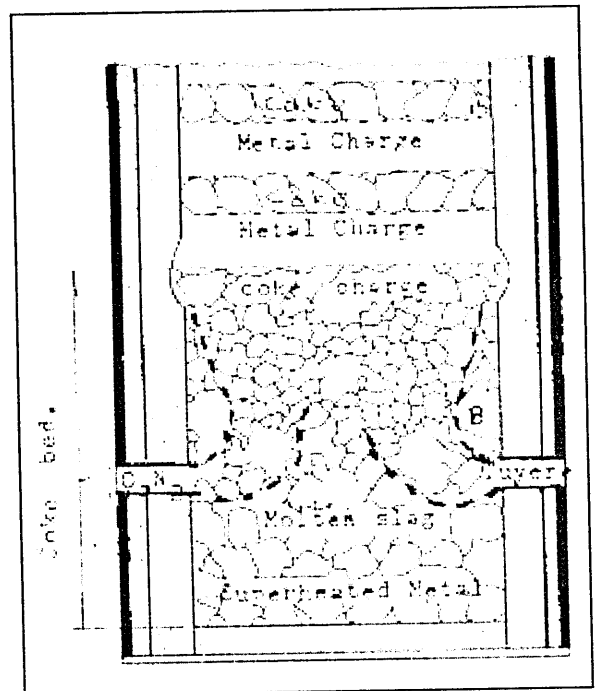


Fig. 2

It has been recognized that various zones of temperature and gas composition exist in a cupola, and these were first delineated by Belden who was

able to determine the upper limit of free oxygen or combustion in the cupola and this gave rise to the well known Belden curve which represents the distribution of the upper limit of free oxygen in the cupola. This limit of free oxygen also represents the limit of heat generation in the cupola and gives a reasonable picture of the super heating zone in the cupola.

In figure 3, the line B - B₁ represents the upper limit of free oxygen in the cupola. This line corresponds also to the upper limit of temperature production because combustion will not continue in the absence of oxygen and the temperature will progressively decrease upwards in the cupola beyond the line B - B₁. The actual zone of maximum temperature is probably immediately below the line B - B₁ where combustion is complete but where a slight excess of oxygen is still present which insures complete combustion.

Line M-M₁ represents a zone of temperature lower than that existing at B - B₁, but sufficient to melt the materials of the charge. Obviously, the charge materials will melt over a range of temperature, the lower melting point materials melting just above M-M₁ and the higher melting point materials melting just below M - M₁. The super heating zone may be regarded as the zone extending downwards from M-M₁ to the tuyere level represented by T - T₁.

As carbon pick-up occurs in this superheating zone cannot be expected to occur readily in the presence of free oxygen below the upper limit of free oxygen viz., Curve B - B₁, it must occur predominantly in the region of the cupola M-M₁ to B-B₁. In the upper portions of this zone, i.e. near the line M-M₁, the temperature is not sufficiently high to favor maximum carbon pick-up whereas in the lower portions of this zone, i.e. near the line B-B₁, the atmosphere may not be sufficiently reducing to favor maximum carbon pick-up.

It may be expected, therefore, that the optimum conditions for carbon pick-up are somewhat near the center of the zone enclosed by B-B₁ at the

lower end and M-M₁ at the upper end. Let us say the optimum conditions occur at the line A-A₁.

In the zone below the limit of free oxygen B - B₁, very little carbon monoxide can exist as free oxygen occurs in this zone. Above B-B₁, however, carbon dioxide formed by initial combination of oxygen in the air with carbon in the coke reacts with carbon to give a certain proportion of carbon monoxide. This reaction is endothermic (absorbs heat) so that above B - B₁, progressing upwards towards M-M₁, the temperature steadily decreases while the proportion of carbon monoxide progressively increases. As carbon pick-up results from the combination of temperature and a sufficiently reducing atmosphere, i.e. a sufficient proportion of carbon monoxide or a sufficient absence of carbon dioxide, it must be presumed that the control of carbon pick-up is intimately associated with the progress of the secondary reaction $\text{Co}_2 + \text{C} \longrightarrow 2\text{Co}$. The exact depth and temperature distribution in this zone will affect carbon pick-up in a major degree.

In the zone below the limit of free oxygen, viz. the zone B - B₁ to T - T₁ conditions could be favorable for decarburization because of the presence of oxygen and the relative absence of carbon monoxide. This zone while beneficial to the temperature of the metal may not be favorable to the carbon content of the metal. This zone will now be referred to as the oxidizing zone, and control of the depth of this zone to prevent loss of carbon could conceivably be just as important as the control of the depth of the carburizing zone.

The position of melting that is the line M - M₁ in relationship to the line A - A₁ representing optimum carbon pick-up is obviously important. As the metal first melts and droplets begin to form these droplets are held by surface tension for some time before they are able to break away and fall down to the well. There is, therefore, at the melting point a prolonged opportunity for the droplets to pick up carbon should the conditions be favourable. If now, the line M - M₁ is relatively close to the line A-A₁, it is reasonable to expect a good carbon pick-up.

THE BELDEN CURVE AND CARBON PICK-UP

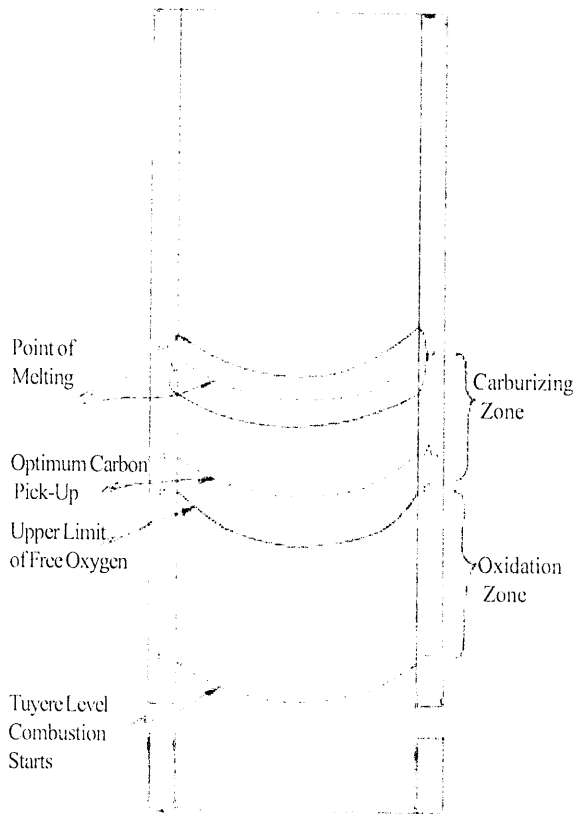


Fig. 3

The various zones of temperature and gas composition in the cupola owe their positions and extent to chemical and physical controlling forces. Thus, the production of initial heat is the result of chemical action but the completeness of this heat production is dependent on physical factors such as blast velocity and blast penetration. Furthermore, the propagation of this heat upwards through the cupola is the result of both physical and chemical actions.

Any temperature that exists above the upper limit of free oxygen is due to the sensible heat of the hot gases ascending the cupola. These gases in passing through the combustion zone pick up heat units which they subsequently transfer to the coke and charge materials which exist above the combustion zone. Evidently, the specific heat and rate of flow of the gases as well as the specific heat of the charge materials will greatly influence the position and extent of the carburizing zone.

Actual melting, therefore, is accomplished by hot gases and the composition of these gases will materially affect the quality of the molten metal.

The Chemical action involved in the carburizing zone is the well known secondary reaction whereby carbon dioxide is converted to carbon monoxide by action on the coke. This action absorbs heat and proceeds very rapidly at high temperatures and very slowly at lower temperatures. The extent of the action is a direct function of the reactivity of the coke. Thus, all other factors being equal, the reactivity of the coke will control the temperature and carbon pick-up during melting.

By carefully controlling both physical and chemical influences in relation to one another, it is possible to melt hot fluid iron and secure adequate carbon pick-up with a variety.

LINING BURNOUT

A practical tie-up between the theoretical zones in the cupola which have been discussed and actual control of the melting process may be found in the nature of the lining burnout.

There are essentially four conditions that might exist and these are schematically portrayed in Figure 4 together with the zone limits that probably exist with each type of burnout.

Type A burnout is a relatively deep but confined burnout located very close to the tuyeres and extends upwards appreciably but is relatively shallow. The degree of penetration is low resulting in an inverted conical belden curve.

Type C burnout starts well above the tuyeres and is quite deep. It extends upwards more than that shown in Type A and is usually founding smaller cupolas (42" and below) where the penetration may be excessive. This gives an upright conical type of Belden curve.

Type D burnout is the most desirable. It starts about 6-9" above the tuyeres and is shallow but quite extensive in height. The Belden curve itself is relatively flat which obviously is superior from the control standpoint.

It is quite evident from these considerations that the degree of penetration of the blast and the velocity of the blast are controlling factors in carbon pick-up. It is also possible to discuss the changes that are necessary to convert the Type A, B and C to that shown in Type D. Attainment of Type D burnout will result in optimum melting and carbon pick-up conditions.

DEGREE OF BLAST PENETRATION

The degree of blast penetration is dependent to the diameter of the cupola, the resistance offered to the blast, and the velocity of the blast. The mechanism of penetration is portrayed diagrammatically in Figure 4. The blast entering the tuyeres in a horizontal direction must change its direction of flow so that it proceeds upwards through the cupola in a vertical direction of flow so that it proceeds upwards through the cupola in a vertical direction. If this is considered firstly in an empty cupola, it is apparent that the initial tuyere velocity is of some importance and must be related to the distance from the tuyeres to the center of the cupola.

Whereas, the tuyere area will control the initial inlet velocity with a fixed volume of air it must be realized that changing the air volume with a fixed tuyere area will correspondingly affect the degree of penetration. Thus, under special circumstances cupolas may be designed with lower or higher tuyere ratios than those given purely on a cupola size basis.

If now, the presence of the coke and cupola stack is given due consideration, it is possible to further deduce the conditions which are favourable or unfavorable to blast penetration.

Consider firstly large coke and an open burden where little resistance is offered to the flow of air in the cupola. Under these conditions, the penetration conditions are essentially similar to those shown for an empty cupola. There is some channelling of the blast but as there is little resistance to flow, the initial tuyere velocity which is determined by the ratio of blast to tuyere opening size, will control the degree of penetration.

TYPICAL BURN - OUTS AND CORRESPONDING RELDEN CURVES

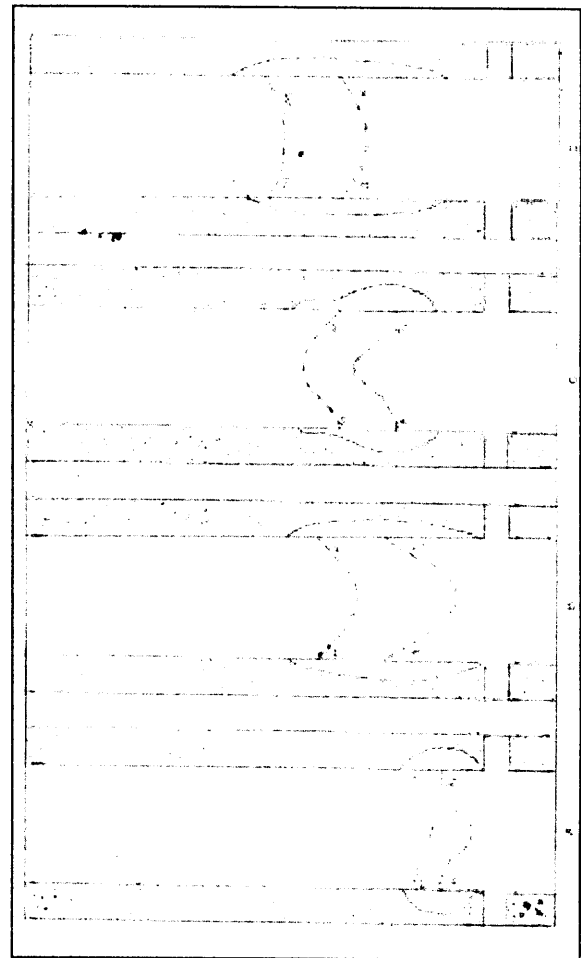


Fig. 4

Under these conditions, the height of the stack can largely control the degree of penetration as any increase in stack with an increase in flow resistance in the vertical direction will, of course, result in increased penetration towards the center, because it is easier in this case for the blast to proceed horizontally. By the same token, a low stack will result in decreased resistance to vertical flow which is turn will result in decreased flow in a horizontal direction, or decreased penetration to the center of the cupola. As the cupola diameter increases, therefore, and penetration becomes more difficult, the burden height should correspondingly be increased to result in improved penetration. In actual practice, however, the opposite condition usually exists and this is one reason why cupolas do not always behave as anticipated.

Consider now where the coke is quite small and the stack is dense. Under these conditions there is at the tuyeres a considerable resistance to the entry of the blast in a horizontal direction by virtue of the frictional resistance brought about by the small voids between the coke. As we proceed upwards in the cupola, the coke size normally increases and the metallic stack is relatively open compared to the small coke being used. As a result, therefore the blast favors flow in a vertical direction with consequent poor penetration to the center of the cupola. Decreasing the burden height in such a case will again favor vertical flow and will result in decreased penetration. Thus, reducing burden to reduce the load on a blower is also against improved penetration.

When faced with small coke the procedure for improved penetration is to reduce the blast used in order to decrease frictional resistance and decrease the tuyere area to provide greater initial impetus to the blast but maintain a high stack to act as a damper in promoting horizontal flow. In many cases, the only logical means of securing the desired penetration is to use eaves over the tuyeres.

BLAST VELOCITY

Some reference has been made to blast velocity as related to frictional resistance to flow and degree of penetration, but some of the more important effects of velocity have not been considered.

As chemical reactions in the cupola are influenced by time they are, of course influenced by the rate of flow or the velocity of the blast. This is discussed more fully in the section devoted to coke combustion characteristics, but in leading up to this discussion, it is well to consider the effect of velocity temperature distribution in the cupola.

The heat generating action of air on coke is confined to the area between the tuyeres and the Belden curve or upper limit of free oxygen. Above the Belden curve, the temperature progressively falls as the endothermic reaction between carbon dioxide and coke takes place. It might be reasoned that as no oxygen exists above the Belden curve not temperature can exist. This is true from the chemical action standpoint but the temperatures

that do exist in the upper portions of the cupola are obtained purely by physical conduction of heat units which are produced in the combustion zone.

Thus, the hot gases travelling upwards from the combustion zone give up as large portion of their heat to the coke and the charge material above the combustion zone. The melting point or zone in the cupola (which occurs above the combustion zone) is located, therefore largely according to the efficiency of this heat transfer from the combustion zone of the cupola.

As this heat for melting is transferred from the ascending gases to the charge material, it follows that the rate of flow of these gases will control the extent to which heat is carried to the upper portions of the stack. If the rate of flow of the gases is high, the temperature will be high at a point well above the Belden curve, i.e. the line $M-M_1$ in Figure 1. If, however, this rate of flow is low, the temperature will be confined to an area not far above the Belden curve. By the same reasoning, a high rate of flow while spreading the heat units over a more extend areas may not result in as high a maximum temperature within this area. This is because the gas may be flowing too fast to give up all its available heat to the charge materials.

As a high velocity blast will raise $M-M_1$ to a point well above the Belden curve, it will also extend the superheating zone. Another feature of high velocity blast must be given due consideration. The high velocity blast results in the raising of the melting zone and results in a lowering of the temperature gradient in this zone. With a lower velocity blast the melting zone is lower and the temperature is more concentrated in this zone. This means in effect that higher velocities will enlarge the band over which the charged materials will melt and will lead to increased difficulties due to dilution and failure to completely, and separately melt all the components of a charge. Higher velocities are, therefore, in the direction of poorer melting control whereas lower velocities result in improved consistency of control. This has always been found to be the case in practice.

CUPOLA BED CONDITION

Unless the bed is well heated throughout its mass,

the zone above the Belden curve will be at a low temperature for some time after the blast is first turned on. This is simply because it will take time to heat this zone by transfer of heat from the ascending gases and at first the carburizing zone will be relatively near the Belden curve. With a sufficiently low initial bed, melting will occur quite near the Belden curve and the metal may be quite cold.

With a high bed, however sometime will elapse before the change can descend to the melting level and during this time normal heating of the zone above the Belden curve may take place. This burning away excess coke will also give slow melting. Slow collection of metal in the well may also lead to colder first iron.

With a hot bed the cupola can start operating very nearly under the condition of balance which it normally arrives at later in the heat. As the zone above the Belden curve is already hot, the ascending gases will give up all their heat to the cooler coke and material and will extend the zone of high temperature rapidly. With a correct height of initial bed under these conditions, it will be found that the initial temperatures and carbons are very closely the same as those found late in the heat.

With a bed that is too low, the solid charge material will come to a zone where free oxygen exists and the melting will occur very close to the Belden curve, the net result is cold iron and low total carbons as well as excessive oxidation of silican and managanese in the charge.

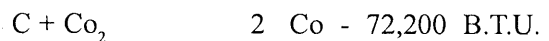
It is apparent from the preceding discussion that certain physical factors such as tuyers sizes, burden height, charge density, coke size, blast velocity, bed height and materially affect the progress of combustion in the cupola and as a consequence the carbon pick-up obtained during melting. Because of these factors it is found that each cupola is a low unto itself and the same coke in different cupolas may often give materially different results. Quite often the physical conditions that exist in a given operation make it quite impossible to utilize a coke of given characteristics successfully. The trick of good melting control with a variety of cokes is the adjustment of the physical factors involved to suit the type of coke being used.

To make this practical it si necessary to have a reliable measurement or estimation of the combustion characteristics or chemical behavior of any particular coke.

Before discussing coke testing and measurement it is necessary to consider briefly the importance of factors such as combustibility and reactivity in relation to the temperature and gas composition zones in the cupola.

INFLUENCE OF COKE REACTIVITY

Coke reactivity may be defined as the rate of reaction of the coke with carbon dioxide to give carbon monoxide according to the equation:



This reaction absorb heat and proceeds very rapidly as the temperature necessary for its progress is raised. It is well known that different cokes vary considerably in reactivity, but is not always appreciated that these differences will profoundly affect the cupola combustion conditions particularly those that control carbon pick-up and temperature.

Consider now the two extreme case viz. where the reactivity of the coke is high and also where it is low.

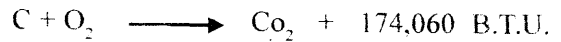
With a coke of low reactivity the reaction $C + CO_2 = 2 Co$ proceeds slowly and the carbon dioxide formed in the combustion zone will rise well above the Belden curve before any appreciable amount of carbon monoxide is formed. The zone A-A₁ which represents the point of optimum carbon pick-up, therefore, will occur well above the Belden curve. In addition to this, because the reaction to carbon monoxide absorbs heat and the reaction is slow, the melting point M-M₁ will be well above the Belden curve. It si also extremely probable that the line A-A₁ will be located very near M-M₁ because the temperature has to be quite high before any appreciable amount of carbon monoxide will form.

As the reaction to carbon monoxide is less affected by temperature than it would be in the case of high reactivity coke, it follows that spreading of the high temperature zone by increased velocities

will not be as harmful. It may be said, therefore, that low reactivity coke promotes a safer and less critical melting condition with respect to blast velocity.

With a coke of high reactivity, the opposite conditions apply. As carbon monoxide will be formed rapidly, the line A - A₁ will be located quite near to the Belden curve B - B₁. By the same method the greater loss in temperature due to the secondary reaction will bring the melting zone M - M₁ down giving a shallower superheat zone. Also, as the reaction is fast at relatively low temperatures, the use of high blast velocities will definitely be harmful.

Coke combustibility may be defined as the rate of reaction between the coke and oxygen to give carbon dioxide according to the reaction.

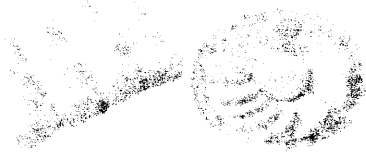


The effects of combustibility alone on cupola zones are considered it may be reasoned that a coke of high combustibility will give an upper limit of free oxygen closer to the tuyeres with a less extensive superheat zone whereas a coke of low combustibility will give an upper limit of free oxygen at a greater distance from the tuyeres with a corresponding deeper superheating zone.

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