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STUDY ON AIR GAP OF BLAST FURNACE HEARTH AND PREVENTION[1]

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Abstract

The service life of blast furnace (BF) hearth can be threatened mostly by air gap. The present paper is set on the investigation of hearth problem and makes analysis on reasons and factors of generating air gap through theoretical calculations and field survey. Effective measures are proposed herein for preventing air gap by well managing every link concerned. It's taken a package solution to realize zero-gap hearth operation and long campaign furnace.

Key words: Long life of BF hearth; Air gap; Design; Maintenance.

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1 FOREWORD

The heat transfer system of blast furnace hearth to hearth life is what immunity system to a human body. Air gap generated in furnace wall symbolizes a signal that some a problem happens to human's immunity, degrading the health and life span. The present paper will focus on the hazards of air gap in hearth wall towards furnace's campaign, the mechanism of gap formation and how to prevent gap and keep a good status of hearth.

2 HAZARDS OF AIR GAP

2.1 Hazards on Heat Transfer System

The following Figure 1 shows calculated comprehensive coefficient of heat transfer between hot metal and refractory when various types of hearth refractory at hot face reach 1,150°C and conditioned at water flow rate 2m/s, refractory thickness 0.6m and different thickness of air gap existent between cooler and refractory cold face. The heat transfer coefficient becomes smaller along with the bigger air gap; the bigger the gap, the closer the curves for those types of coolers. Being the greatest factor and much greater than cooling type and water rate to affect hearth heat transfer capacity, the air gap impairs severely the intensification of hot metal circulation withstood by hearth.

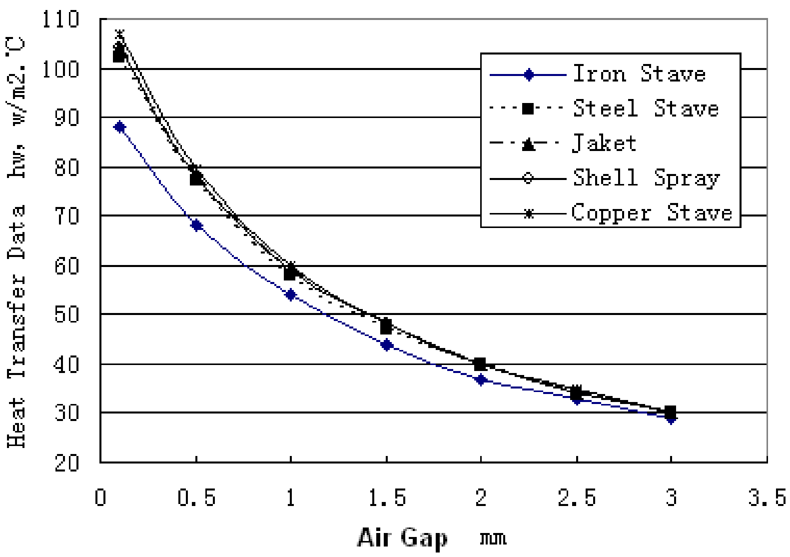

Figure 1. Relationship between HM Comprehensive coefficient of heat transfer (in-furnace intensification) and air gap thickness.

2.2 Basin of Leaked Water from Hearth

The water leaked from tuyere and cooler and arriving in hearth will be gathered at the air gap beside cooling stave. Proceeding with the furnace production, gas will enter the gap; carbon block and gas will derive heat energy to evaporate the water, which will be expanded in volume, thus expanding further the gap, suffering the heat transfer capacity of furnace wall. And the moisture remained in air gap will lead to etching to brick seam and ramming material, again expanding the gap and deteriorating hearth status.

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2.3 Accelerating Fall-off of Hearth Skull

The IJmuiden No.7 blast furnace [1] is found out that large quantity of carbon powder is settled between carbon block and skull. Analysis tells that the steam and iron catalyze decomposition of CO at proper temperature to produce graphite powder at hot face of carbon block. Graphite powder is loose and has very bad thermal conductivity along with great lubricity. Thus its existence at hot face of carbon block could result in skull falling and arrest re-generation of skull.

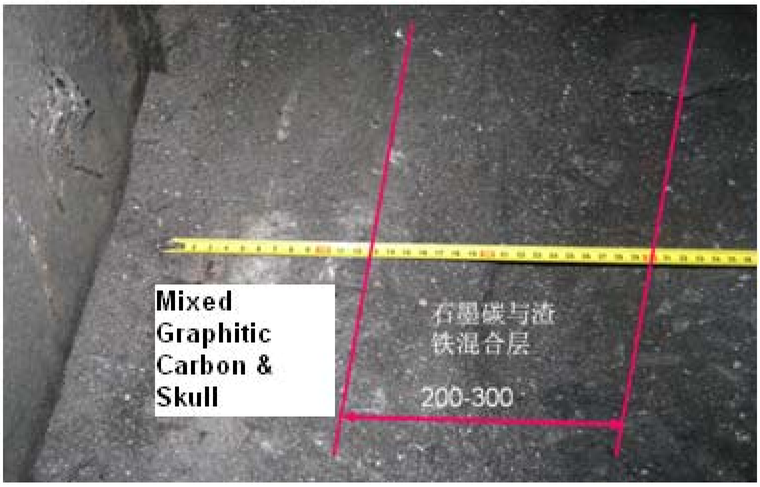

Figure 2. Mixed graphitic carbon powder and skull on hot face of carbon block of China's Meishan No.3 BF hearth.

Investigation has been done to the "elephant area" of Meishan No.3 BF hearth, finding out that large quantity of graphitic carbon was precipitated at hot face of carbon block, forming mixture of graphitic carbon and slag-iron as thick as 200~300mm.
Carbon deposit will damage not only carbon block but concentrate between carbon block hot face and skull, to a certain degree, loosen skull off.
Existence of air gap, collection of water and passing of gas and steam through furnace wall provide proper material condition for graphitic carbon to settle down at hot face of carbon block.
Frequent shutdown and re-blow of blast furnace can cause the change of pressure in air gap, in which, the air respires outwards and supports the formation of air passage. If BF is sealed, carbon deposit can usually be balanced when CO is exhausted. However, the fact is BF is never sealed; in practice, when opening the taphole, CO is leaked, which lets the "fresh" CO continuously pass through refractory, quickening the deposit of carbon and resulted in brittle carbon block and falling of skull [2].

3 MECHANISM OF AIR GAP GENERATION

3.1 Furnace Shell Subject to Inner Pressure and Elastic Deformation

The furnace shell will be engendered elastic deformation due to the inner pressure, and result in expanding diameter during operation. The formula for thin shell theory is:

$$\sigma=P(D_i+\delta_n)/(2\delta_n\Phi)$$

In which, σ– stress of furnace shell, P – inner pressure onto shell, Di – shell ID., δn– shell wall thickness, Φ– weld coefficient.
When P=0.45MPa, Di=17,600mm, δn=60mm and Φ=1 (double-sided penetration

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welding), it gets σ=66.2MPa. When the openings of cooling stave is considered, the average stress of the water pipe hole will reach 126.7MPa (based on 60-piece staves, 240 heads, 110mm hole diameter).
According to Hooke law, σ=εE (ε- stress, E – elastic modular of furnace shell); ε=σ/E=126.7/196,000=0.0647%.
From the above calculation, it's known that at the water pipe holes of the shell the expansion at axial direction is 11.4mm and the circumferential expansion is 35.8mm. Meanwhile, at the other parts of the shell the axial expansion is 5.9mm and the circumferential expansion is 18.7mm.
Normally, the expansion coefficient of hearth brick is about 3.5E-6(1/°C). Suppose the average temperature of the refractory is 300°C and OD. of hearth brick is 17,000mm, the expansion of hearth brick in axial direction will be about 17.8mm.
Design of hearth expansion joint shall consider the shrinkage that equals the expansion of carbon block minus expansion of shell elastic deformation, that is, 17.8-11.4=6.4mm.
If expansion of refractory is directly transmitted to shell, the furnace shell is easily cracked. That's why expansion joint is designed for shrinking the expansion of refractory. For large block, expansion joint is considered as 80~100mm, filled with carbon ramming mass, more importantly, meeting the needs of ramming construction. In case that the expansion joint of that width is not rammed tightly, the shrinkage would be much larger than the needed expansion of carbon block; the consequence would be that the expansion of block after heat-up could not force ramming mass to closely appressed to cooler and further expanding outwards along with furnace shell; finally, between the cooler and ramming mass would be spaced for the air gap.
Following Figure 3 shows the relationship of recorded shell expansion and blast pressure by strain-foil test on hearth below taphole for IJmuiden No.7 blast furnace[1]. Herein jacket cooler is applied for hearth, graphite brick closely hugged onto shell. It's indicated that the circumferential expansion of shell has reached maximally 40mm, at blast pressure of about 0.4MPa. The calculation presents that under pressure of 0.4MPa blast, the expansion of shell diameter is about 4.5mm and circumferentially about 14.2mm; however, the recorded circumferential expansion of shell has reached 15~40mm. Such expansion arisen from pressure beyond normal inner pressure should have been transmitted from the heated carbon block to shell; namely, expansion of block brings about further expansion of shell outwards. In this case, carbon block can be always clinging to shell, no chance to have air gap in wall. But one concern is if the shell would be cracked. According to Hooke law, the shell stress in average reaches 153MPa when shell circumferential expansion is 40mm, which is still within the allowed stress range, and will not happen plastic deformation or cracking.

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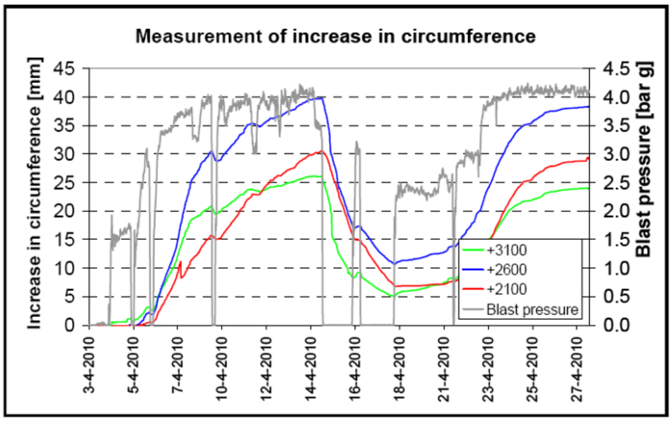

Figure 3. Shell Circumferential Expansion and Blast Pressure Since Blow-in[1]

For hearth with jacket cooler, the shell has no openings weakening the strength. Therefore it can withstand the inner stress brought about by carbon block expansion and in safe limit. The refractory clings closely to shell and expands outwards, effectively against air gap, ensuring the hearth heat transfer capacity. For hearth with stave, the shell has openings of water pipes for weakening strength to withstand the inner stress, which is especially at opening 2 times of non-opening. The shell is even harder to bear the refractory expansion; in design shall not consider transferring expansion stress of refractory onto shell. If expansion joint absorbs too much of expansion, the air gap would easily emerge between cooler and refractory, weakening the heat transfer capacity of furnace wall.

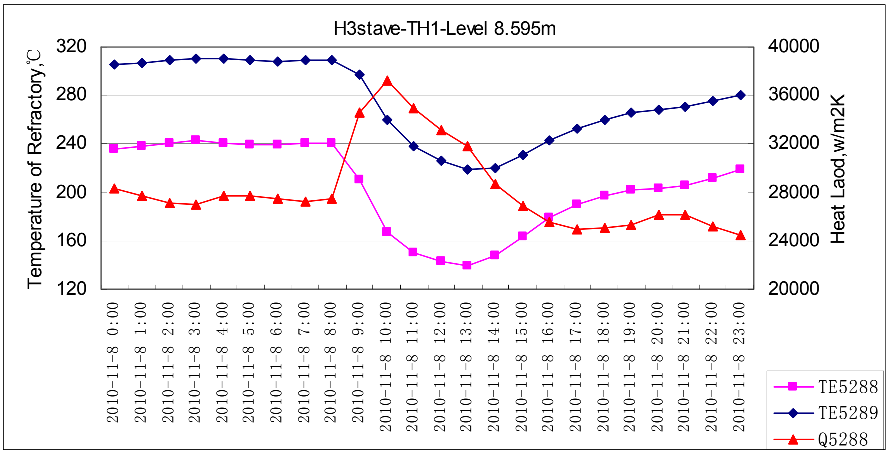

Figure 4. Record of Hearth Refractory Temperature and Furnace Wall Heat Load.

Figure 4 shows the variations of refractory temperature in front of H3 stave below taphole #1 of one BF and heat load from furnace wall during shutdown and re-blow. At early stage of shutdown, refractory temperature decreases, but heat load of hearth wall rises up obviously. Later, due to furnace stop, heat exchange inside furnace is faded, and then heat load is seen gradually downwards. Why does the heat load of hearth wall increase during early shutdown period? It's got from above analysis and calculation that elastic deformation of shell results in air gap between refractory and stave. During shutdown, furnace is relieved pressure; the elastic deformation of shell vanished; temperature of refractory down, but which is later than decrease of inner pressure of furnace. The gap between refractory and stave becomes smaller; stave comes closer to refractory, and heat load from wall is increased. Subsequently, hot

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metal inside furnace flows weakly; the heat transferred from wall also is decreased. During re-blow, inner pressure is up; temperature rise of refractory lags behind inner pressure; the gap between refractory and stave is wider, so, the heat energy from wall is contrarily decreased. It fully reflects the rule of air gap variation at that zone. Refractory will not be attached closely to stave along with shell's elastic deformation, leading to existence and change of air gap in that way. This can be witnessed in some other records or trends analysis of hearth temperature of similar furnaces. Generally speaking, the air gap generation has much to do with the imbalance between refractory expansion and shell's elastic deformation.
In that sense, it's recommended that before startup of a new BF, strain foil can be put on shell below taphole to detect shell deformation and stress change trend, hereby to infer the possibility of air gap existence in wall, significantly reminding the status of hearth in furnace operation.

3.2 Incomplete Drying-out or Hearth Water Leakage

Drying-out is to transfer heat energy from furnace inside to outside, meanwhile to drain water from furnace inside to outside. A large amount of water will be collected in refractory in front of stave if failing to open grouting hole of hearth and rise temperature of refractory hereof to desired level. The water remained in wall is evaporated by the huge heat from furnace after blow-in, normally 1kg water evaporated to $1.25m^3$ steam, volume expanded by 1,200 times. Such steam will boost the pressure between stave and refractory, forcing them to give rise of gap. Steam escaped and gas pass-through in the gap will expand the gap further, severely damaging wall's heat transfer system. Such gap will also be the basin to contain hearth-leaked water, which can be evaporated by the heat from hearth to further develop the gap. A great deal of steam will, additionally, damage mortar, carbonize block, deposit graphitic carbon on hot face, and finally fall off skull. Refractory at taphole is the thickest, collects most water, hardest to be dried. With the production process of furnace, water is dried; gap makes the time for existence between taphole refractory and cooler; the gap again collects new water; water and gas co-act on hot face of refractory to cause much carbon deposit and peeling of skull; that is how severely the furnace wall in that zone. Even more is erosion of rotary washing by the hot metal at taphole and mud drum. It can be understood one of the important reasons that air gap is arisen at taphole area and high-temperature refractory and excessive erosion.
Incomplete drying-out cannot have the ramming mass and refractory in front of stave rise to drying temperature; after blow-in, gas and water are to be faded away under the role of etching; that lead to air gap and its development.
Presently, most blast furnaces keep their refractory before stave at pretty low temperature even after blow-in. A large volume of water in ramming mass cannot be dried in time, in addition, the temperature of ramming mass and mortar are also lower than the drying temperature; all these leave non-ignorable risks on campaign life of blast furnace.

3.3 Defective Construction of Refractory

Other factors, such as not retainable quality of carbon block mortar, not following instructions for construction, not fully packed mortar and not properly controlling block seam, will give rise to air gap. Concretely, the construction of ramming mass in front of

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stave may be not tightly and densely if failing to follow construction requirements, thus easily producing unqualified expansion joint; consequently, carbon block may not be expanded to be desirably close to stave; in between may appear air gap.

3.4 Clearance between Staves

There are a large amount of clearances existing between staves of hearth, which are difficult to be rammed or rammed solidly. Incomplete drying-out makes the chance for etching from steam and gas after blow-in, due to which, the gas passages are formed, and furthermore, air gaps are formed at hot face of stave. Besides, grouting between stave and shell, if improperly selected, can corrode the filler between staves and ramming mass and mortar as well to form air gap. Still, cooler type of hearth, refractory variety and construction activity and some uncontrollable factors make the real situation more complicated. For instance, the grid cooler will have only one regular expansion joint or contact between refractory and shell, which is better controlled. Therefore, from the perspective of control on hearth air gap, the grid cooler proposal promises more than cooling stave.

3.5 Selection of Grouting and Pressure Control in Maintenance of Hearth

Air gap problem in hearth will never be solved very well by using the grouting of high volatility, unstable volume, low conductivity and solidification during production. Some blast furnaces in China select high-volatility grouting which cannot quickly solidify in the hearth condition, instead easily volatizes, so that not long after mud jacking, the furnace wall takes place air gap by the etching of gas, repeatedly rising the wall temperature, seemingly hardly taken a radical cure.
Mud jacking for hearth maintenance entails strict control of pressure; once out of control, it would not drive away air gap, even worse, drive on damage of hearth and burn it out. Blind operation of mud jacking considering no control of pressure will press the block seam loose to release more gaps, threatening the hearth life.

4 MEASURES TO AVOID AIR GAP

4.1 Proper Cooling Type and Expansion Joint

Grid cooler characteristic of high cooling efficiency and easy control of joint between wall and shell will be more favorable for preventing the air gap of hearth. No opening on shell will be stronger to bear the refractory expansion stress, and more favorable to attach refractory closely to shell and keep effective heat transfer. Most blast furnaces in Europe and North America prefer grid cooler, thus succeed in long campaign life. Practice proves that grid cooler should be best of the better in terms of zero-gap hearth operation. Admittedly, other types of coolers can also succeed in long life target if only effectively controlling every link concerned.
For installing the hearth refractory as closely as to shell or stave, the elastic expansion of shell shall be taken into account for construction of expansion joint. Shell stress and expansion joint of refractory shall be combined to realize wedding between refractory and cooler for ensuring zero-gap hearth.

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4.2 Construction Details

Firstly, installation of furnace wall equipment shall comply with regulations, requiring firm stationary contact, tightly sealed bolt hole and water pipe opening on shell, all of which counteracts gas leakage. Secondly, refractory building and mortar use shall strictly follow the drawings and makers' construction instruction; mortar shall be built fully, with no bubble or gap, against from oversize of block seam or even triangle seam; mortar expels out from the densely-compact block seam to its desired size; ramming mass shall be filled tightly according to construction requirement. Thirdly, due care shall be treated on completed refractory, free from brickwork vibration or crack.

4.3 Complete Drying-off

Grouting hole is opened and hot water used for drying off, one of the important links of pursuing hearth life. The grouting hole shall be all open to drain gas. On furnace bottom plate shall install water drainage pipe, which is open to discharge water and steam arisen in drying-off. It doesn't mind flowing out the refractory mortar from the grouting hole because it's forced out by expansion of wall refractory, no gap left on wall. Even if excessive mortar is flown away, it can make up after blow-in or at first regular maintenance of furnace. What is to do in drying-off is to fill water in the cooler and stop pump and heat exchanger; then open the pump and heat exchanger according to the water temperature level. It's to ensure the refractory temperature in front of stave should reach 110°C, at which the mortar and ramming mass can possess certain drying strength.

4.4 Blow-in Details

Two points shall be paid attention in blow-in. One is the run-in time of furnace. During this ramp-up period, it's wise to control tempo and let the early slag form stable skull; then as the output is increased, the hearth can have adequate immunity. Proper intensification at early stage of blow-in will give a running-in time for hearth refractory, expanded fully and evolved in physiochemical process, thus laying good foundation for hearth zero-gap operation and long life. The other is hot water blow-in. In the beginning, the hearth is protected by refractory that carbon block is not eroded; however, to completely drain off water from cold face of wall and let mortar and ramming mass solidify in quickest time, it's suggest rise up temperature of cooling water of hearth in the first one month of blow-in, in this way, refractory beside stave can reach 110°C, the drying temperature, thus reducing the possibility of air gap in wall in future operation; after such one month, the cooling water temperature is recovered to its normal level.
During the blow-in and re-blow process, operation at normal pressure should be done first; when the hearth refractory is expanded for heated, the pressure is then increased to attach refractory closely to cooler, against from air gap between cooler and refractory.

4.5 Strict Maintenance of Production

Regular maintenance at early stage of blow-in would better open the grouting holes of hearth for inspecting the gas and water vent. And in time the grouting operation can

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be carried on under strict control. The air gap and gas line if possible at cold side of hearth wall can be filled densely without delay. Zero-gap hearth can be realized through this measure.
Grouting of hearth must be strictly controlled, low pressure and low flow. Pressure gauge is recommended installing at grouting hole to control the activity of mud jacking. Carbon press-in mortar with silica-solved binder is preferred as grouting mass, which is ensured good thermal conductivity and volume stability; worthy of attention is never used grouting mass of high volatility. In view of bearing capacity of shell and carbon block wall, it'd better keep the pressure at grouting hole within 1.5MPa, at most 2.0MPa. Mud jacking is at best conducted during shutdown of blast furnace.
At the medium and later stage of furnace campaign when hearth refractory is eroded seriously, it will not be the time for mud jacking work. The wall becomes very thin, weak to resist pressure; once mishandling, the brickwork may be easily pressed loose and destructed. Gas should be also kept an eye from leakage; if detected, the leaked point shall be repaired welding to present gas from etching on refractory to form air gap.
One of the important aspects in long campaign is to restrain water from cooler. Survey finds that most hearth accidents have something to do with water leakage. Leaked tuyere shall be timely changed, especially better management of tuyere life, advisably to change the duly-served tuyere. Dual-cavity tuyere should be an efficient measure to enchance tuyere life, capable of averting hearth water leakage and lessening shutdown ratio. Take CST No.1 BF as an example. It was designed for 8-year life for the lower quality of hearth refractory; multiple measures including those mentioned above were taken; presently it has been running for 28 years, expected to 2013. Elaborate operation and maintenance of hearth are critical to the success.

5 CONCLUSION

To stop and prevent air gap is significant for hearth long life. Complete measures are preconditioned in design; every link of installation is controlled, free from possibility of air gap. Temperature of furnace wall is risen appropriately in drying-out to slowly evaporate moisture and solidify the mortar. Intensification process is managed in early blow-in to give adequate time for expansion of hearth refractory, forming, drainage of remnant moisture and evolvement of bulk refractory performance; it means a run-in time for a new furnace. Maintenance of hearth can also attend to emergence of air gap. With the good control of air gap, the heat transfer system of hearth can display reliable and sustainable performance, thereby, the skull can take a form reliably to protect hearth.
The key issues to achieve long life BF are described as well-considered design, construction quality, complete drying-out, well-controlled blow-in tempo, well-managed hearth water free from leakage stable running, and correct maintenance of hearth. Success in all these aspects would have long campaign of blast furnace come true.

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