Technology of Ironmaking
(Study Support)


Ostrava, 2015
Title: Technology of Ironmaking

Code: 618-3002

Author: Ján Kret

Edition: first, 2015

Number of pages: 55

Academic materials for the Metallurgy Engineering study programme at the Faculty of Metallurgy and Materials Engineering.

Proofreading has not been performed.

Execution: VŠB - Technical University of Ostrava
STUDY REGULATIONS

For the subject “Technology of ironmaking” in the 2\textsuperscript{nd} semester of the branch “Modern Metallurgical Technologies” you have obtained an educational packet including integrated lecture notes for the combined study comprising also study regulations.

Prerequisites

Graduation from the subject “Theory of Processes in the Production of Iron and Steel” is a minimal prerequisite for the study of this subject.

The objectives of the subject and outputs from the education

The aim of the subject for students is to acquire broad theoretical and practical knowledge of the technological principles of production of agglomerate and pig iron, of structural and technological nodes of the blast furnace plant and to understand and know how to apply relationships describing theoretical principles of metallurgical processes.

After studying the subject, a student should be able to:

Acquired knowledge:
- the student will be able to apply the theoretical knowledge in real operating situations
- the student gets a comprehensive look at the process of the production of pig iron

Acquired skills:
- the student will be able to solve the tasks, pointing to the optimization of the production of pig iron
- the student will be able to respond to the specific deviations of blast furnace working and analyze their causes

For whom the subject is intended

The subject falls within the Master’s study of the branch “Modern Metallurgical Technologies”, the study programme “Metallurgical Engineering”, but it can also be studied by applicants from any other branch, on condition of having met the demanded prerequisites.

Recommended procedure for studying each chapter:

At the beginning and at the end of each chapter, there are instructions for students to follow. At first, the student has to realize the main goals and the structure of the studied topic. After reading over and studying the topic, the gained knowledge and skills need to be checked, possibly a given task needs to be solved.

A way to communicate with lecturers

To gain credits, a semester project must be elaborated on a specified topic. Topics for the projects and detailed instructions for their elaboration will be discussed with students at the beginning of the course in which students will be present. A date and place of consultancies will be announced. Consultancies are possible even by phone and e-mail. The semester project will be evaluated before the examination.

A contact to a lecturer: office - A522, telephone - 697324464, e-mail – jan.kret@vsb.cz
1. RAW MATERIALS FOR PRODUCTION OF AGGLOMERATE AND PELLETS AND THEIR PROCESSING

Subchapters:
- Raw materials for production of agglomerate and pellets
- Requirements for the ore part of the charge, fuels and alkaline additives for production of agglomerate
- Technology of agglomerate production
- Management of agglomeration equipment productivity and agglomerate quality

Lecture

Raw materials for production of agglomerate

The main purpose of sintering of iron ores (agglomeration) is to convert fine raw materials into lumpy material for pig iron making in the blast furnace. The properties of the original raw ore are changed in this process. The charge for agglomerate production comprises three basic parts.

a) The ore part of the charge consists of agglomeration ores and iron ore concentrates. Agglomeration ore is fine natural raw material (iron ore dust) of granularity below 10 mm. It has usually a relatively lower iron content (below 60%). A concentrate is a product of iron ore concentration. It has a higher iron content (above 60%) and lower granularity (below 1 mm). A higher concentrate proportion in the ore part of the agglomeration mixture increases richness of the produced agglomerate, however, it can decrease productivity of the agglomeration belt and increase dust particulate matter emissions to air. Iron containing dust waste forms a large proportion of the ore charge. These are mainly dusts collected from de-dusting systems and sludge generated in metallurgical and other industrial branches. Their proportion is limited by a content of harmful elements, mainly zinc, lead, cadmium, alkaline compounds, non-ferrous metals etc.

b) Agglomerated coke is a fine fraction of produced coke of granularity 0 to 3 mm. Exceptionally anthracite is used as a coke substitute.

c) Base additives comprise dolomitic limestone, limestone, possibly dolomite. Their function is to ensure satisfactory basicity of the blast furnace charge, so that addition of lumpy basic additives into the blast furnace can be minimized. A part of additives can be charged in a form of calcined lime. Thus amount of heat needed for dissociation can be decreased and mainly water surface stress changes and capillary forces, wettability and sinterability of the sintered mixture increase (agglomeration equipment productivity).

Requirements for the ore part of the charge, fuels and alkaline additives for production of agglomerate

The ore part of the charge

Agglomeration ore is supplied in granularity below 10 mm. Grains larger than 10 mm are not advisable, because heat transfer from the grain surface inwards is too high. There is low
temperature on the grain surface, melting does not occur and the grain does not fuse with other grains.

Coke (fuel)

Coke burning is the main reaction of the sintering process. Heat, occurring in this reaction, ensures formation of the melt needed to fuse the particular ore grains. Besides heating the charge by coke burning, heat exchange occurs in the sintered layer, too. The agglomerate is heated by combustion air in the upper part and hot flue gasses transfer heat to the sintered charge under the sintering zone. Two thermal waves go through the agglomeration layer. One caused by coke burning, the second one by heat exchange. If velocities of the particular thermal waves differ too much, extension of the sintering zone, a maximum temperature decrease and a decrease in a move of the flame front occurs.

Both the thermal waves should proceed approximately at the same velocity (in phases). As the heat exchange velocity cannot be controlled, we control the coke burning velocity. Because the burning velocity depends on the specific surface size of material grains, the coke burning velocity is controlled by its grain size change.

For coke, the $H_1$ flammability value is about 1 mm, $H_2$ flammability is approximately 3 mm. For anthracite, the optimal granularity is 1 to 2 mm (lower porosity), for charcoal 2 to 4 mm.

![Fig. 1 Agglomerate production scheme](image)

1 – storage container for coke, ore and limestone, 2 – water feed, 3 – the first stage mixing drum
4 – the second stage mixing drum, 5 – batching feeder, 6 - ignition head, 7 – sintering conveyor belt,
8 – agglomerate crusher and screener, 9 – exhausting pipeline, 10 – electrostatic dust collector, 11 - exhaustor
**Base additives**

Base additives should be of granularity below 3 mm. The particular grains of basic additives are in the first phase subjected to dissociation, in the second phase the dissociation product CaO reacts usually with SiO₂ from the molten surface of ore grains. As the above mentioned reactions last for a certain time and the sintering process is fast, the central part of the original grain remains not-reacted as free CaO. Lime absorbs moisture from air and agglomerate disintegrates.

**Technology of agglomerate production**

Figure 1 shows a scheme of operational continuous process of the agglomerate production on the sintering belt.

A mix of agglomeration ore, fine grain concentrate, additives and fuel is moisturized with water prior to sintering. This is then pre-pelletized in a nodulizing drum in order to reduce the fine grain part proportion and enhance permeability of the mix. The pre-pelletized mix is put on a sinter machine in two layers; the upper layer is ignited by a strong external heat source, air is sucked from the bottom of the bed layer and fire penetrates the mixed material gradually in the other parts of the layer, in the direction of the sucking air, thus converting the mix into sinter, followed by cooling. Burning temperature is typically maintained between 1300 to 1500 °C.

The sintering process is completed upon burning-out the fuel above the grate. Agglomerate leaves the sintering equipment, then it is crushed into smaller size, screened, cooled down and transported by a conveyor belt into blast furnace bunkers. When screening, a certain proportion of fine and dust fraction is separated to be re-used, the so-called return agglomerate. This return agglomerate, amount of which is about 25 %, is added to the agglomeration mix and re-sintered.

**Management of agglomerate equipment productivity**

On condition of a constant composition of the feed-sinter and at the same technology of agglomerate production, the quantity of the produced agglomerate is directly proportional to the sintering belt speed \( v_{SP} \). In operational conditions the belt speed must be regulated according to technological changes and composition and properties of the sintered mix.

If the sintering belt speed is too high, sintering is not completed at the end of the belt. The move of the sintering zone (flame front) ends in a certain distance above the grate surface. Agglomeration mix under this area is not sintered, only dried and goes back to the charge as a part of the return agglomerate. This fact dramatically decreases the agglomeration belt productivity and destabilizes further sintering process.

If the sintering belt speed is too low, sintering finishes far before the end of suction area and productivity drops down sharply.

Therefore the sintering belt speed is controlled, so that sintering can be completed just before the end of the belt, typically above the last but one exhaustion chamber.

Identification and control of the position of the end of sintering is the first presupposition for management of the agglomeration equipment productivity. To control and regulate the place where the flame front touches the grate area, the position of the maximum flue gas temperature under the grate, the position of maximum illumination of the grate (photocells) and CO₂ content decrease in flue gas is used. After meeting the requirement for stabilization of the end of sintering, the equipment productivity management analysis can continue.

As seen in Figure 2, for the sintering belt movement must apply:

\[
\frac{L}{h} = \frac{v_{SP}}{v_{FH}}
\]
As the sintering belt length and the sintered layer height does not change in operation, the sintering belt speed can be expressed:

$$v_{SP} = \frac{v_f h * L}{h}$$

The sintering belt speed depends linearly on the speed, at which the flame front moves from the surface area down to the grate. At non-changed construction conditions, it depends on parameters affecting the flame front movement velocity.

The flame front velocity mostly depends on burning rate of fuel (coke dust). At the same combustibility of the used fuel and its granulometric composition, the fuel burning rate depends on oxygen feed intensity into the flame front zone. As the oxygen feed to the burning place is ensured by air sucking through the sintered layer, the burning rate depends on voids content in the layer, on its permeability.

![Fig. 2. Dependence of the sintering belt speed on the flame front movement speed](image)

As the grain layer permeability could not be determined continuously in operation so far, it is mostly replaced by the value of pressure loss in the grain layer (pressure difference).

Commonly for the pressure difference calculation the so-called Ergun equation is applied. The formula implies, that the pressure difference can be decreased (permeability increased) more or less mainly by increasing the mean grain diameter of the charge and by improving the grain shape coefficient ($\phi$). The voids content ($\varepsilon$) is determined by the given values. The decisive significance has the nodulizing drum function, i.e. formation of micro-pellets in the second stage of mixing of the agglomeration mix. The sintering belt productivity is then controlled by feeding water into the second stage drum. Nowadays, a dependence curve of moisture – permeability of the agglomeration mix is determined by measurements. The mix moisture is kept just before the given curve maximum by precise water feeding. Operation on the top of the curve would be risky due to the possibility of over-moisturizing the mix.

However, the optimal moisture of the agglomeration mix changes its value and position depending on the mix composition (homogenization piles), and also on the return agglomerate proportion, its temperature, a condition of grates and so on. Therefore, for the precise control of the sintered mix permeability it is necessary to measure continuously both the parameters – moisture as well as permeability of the mix and to update the current position of the curve maximum and to control the amount of the fed water this way.

**Management of the produced agglomerate quality**

Reducibility and strength are the essential quality parameters of the produced agglomerate. As the agglomerate strength decreases, while reducibility increases, and vice versa, the agglomerate quality management is searching for a compromise between these parameters. Because the actual strength and reducibility values usually are not known, substitute indicators are searched for. The fact that the agglomerate quality depends mostly on
the thermal regime, i.e. the amount of fuel in the charge, is used. At a high fuel content, high amount of heat is in the layer, and more sinter forms. The sinter after solidification creates strong bridges between grains – strength increases. However, the sinter fills pores, the specific surface reduces and reducibility decreases deep down. On the contrary, the low fuel content in the charge causes the production of agglomerate with lower strength, but high reducibility.

A rate for the agglomerate strength can be the return agglomerate amount (agglomerate fraction below 6.3 mm). When the amount of the formed return agglomerate increases, this means, that strength of the finished agglomerate decreases and reducibility increases, and vice versa. Then, a proportioning bin needs to be built for the return agglomerate and its weight needs to be controlled (by weighing) or the return agglomerate height level in the bin needs to be monitored. When the return agglomerate weight in the proportioning bin decreases, this means that strength increases and reducibility decreases. An operator has to reduce the fuel and quality parameters return to their initial values.

Questions:

1. What is the agglomeration charge composition?
2. What granularity of agglomeration ore, basic additives and coke is used?
3. What does the coke granularity for sintering depend on?
4. What are indicators for management of the agglomeration belt productivity?
5. What does the agglomeration coke burning rate depend on?
6. What is the Ergun equation used for?
7. What is the relationship between moisture and permeability of the agglomeration mix?
2. RAW MATERIALS FOR THE BLAST FURNACE PRODUCTION OF PIG IRON

Subchapters:

- Raw materials for the blast furnace production of pig iron
- Requirements for quality of raw ore, coke and base additives

Lecture

Raw materials for the blast furnace production of pig iron

Ore charge for the blast furnace production of pig iron comprises mainly agglomerate and pellets. At present, ore charge consists approximately of 70% of agglomerate and 30% of pellets. Agglomerate has the advantage in comparison with pellets, that it is alkaline and has high strength in reduction, while pellets have an ideal shape and a higher iron content. Exceptionally, raw ore lumps are used, or steel plant slag, which substitutes even for a part of slagforming additives. However, the steel plant slag addition noticeably increases phosphorus content in pig iron, therefore is used only at minimum extent. Steel scrap (scrap iron) is also used as a charge material, mainly for production of foundry iron with low phosphorus content. Even manganese ore is also charged to the blast furnace. From economic purposes, its use is only limited for campaigns at technological failures in the hearth (hearth ingrowth) to reduce viscosity.

Blast furnace coke in the blast furnace acts as a deoxidizing agent, fuel, carburizer and a “column skeleton”. Recently, a part of conventional blast furnace coke has been replaced by coke fines (below 30 mm), charged along with the ore charge. The specific amount of this coke reaches up to 100 kg per 1 ton of pig iron. Only exceptionally a part of coke is replaced by high quality anthracite.

Base additives in the blast furnace ensure formation of slag of required composition and properties. Mullock and coke ash are acidic, additives are always alkaline. The following additives are used in particular: limestone - \( \text{CaCO}_3 \), dolomitic limestone - \( \{\text{Ca Mg}\}_{\text{CO}_3} \), dolomite - \( \text{CaMg(CO}_3)_2 \), in case of need ankerite - \( \text{Ca}[\text{Mg,Fe,Mn}]_{\text{CO}_3}_2 \).

Requirements for quality of raw ore, coke and base additives

Ore charge

Requirements for raw ores are based on a requirement for minimal costs for pig iron production with the use of the given raw material. Individual properties cannot be assessed separately, but in a close relation to other properties.

Chemical and mineralogical properties

Chemical and mineralogical properties of raw materials are given by their chemical composition and amount and distribution of particular mineralogical components.

The definition of basicity (alkalinity) also comes from chemical composition. Narrow basicity \( (B_1) \) and basicity \( (B_2) \) are used.

A content of harmful substances belongs to chemical properties, too. Some substances are considered harmful, as they interfere the run of the blast furnace process, for instance zinc,
lead, alkaline compounds, chlorine etc. Most of harmful elements are undesirable, because they decrease quality of the steel manufactured from the given pig iron (sulphur, phosphorus, arsenic, non-ferrous metals, etc.). Harmful element categorization depends on a kind of the manufactured steel.

Mineralogical properties of raw materials are characterized by a shape and size of mineral components (ore structure) and their spatial distribution (ore texture).

**Physical properties**

Raw ore moisture content relates mainly to its structure and granularity. Hygroscopic water adsorbed on lump surfaces and in pores makes manipulation with the raw material difficult. In winter season excessive moisture results in freezing of imported ores and a need for their de-freezing. Moisture affects also loose (bulk) properties of raw ores. Chemically bound water increases the specific consumption of coke. However, hydrate water is mostly removed during ore heat treatment prior to the blast furnace processing.

For the use directly in the blast furnace, the optimal granularity of raw ores is 10 to 60 mm. An analysis of the granularity influence on permeability of grain materials implies that the blast furnace charge should not contain materials of granularity less than 6 mm.

In operation, the granularity variance (granulometric homogeneity), which has to be as low as possible, is of a high importance for the ore charge layer permeability. The raw ore density is the ore sample weight to volume ratio. It is necessary to determine a real, apparent (volume) and bulk density.

Out of the bulk properties, the most important is the angle of discharge, a knowledge of which is used for the work of dumping equipment of blast furnaces and when designing ore dumps.

Porosity of raw materials is defined as a volume not filled with solid matter proportion from the total volume of the raw material lump. A number of pores in a volume unit and their size are characterized by the specific surface, which determines the reaction surface size, on which reducibility depends in particular.

**Technological properties**

**Strength characteristics**

Compression strength of raw ores is actually determined only for pellets, it is expressed by force at which a pellet ruptures and units are Newton/pellet.

The most widespread is the strength testing in abrasion, which is normalized in terms of ISO. It is performed in a drum similar for MICUM test, but of 0.5 m width. Strength is determined by a proportion of grains larger than 6.3 mm. “Wear” as a proportion of grains below 0.5 mm is evaluated, too.

**Reducibility of raw ores**

Reducibility is a name for the velocity of iron oxide transformation to metal by effect of reduction gas, or also a time needed for a complete iron oxide reduction. The value of the reduction rate is the metalline charge weight loss per a time unit. The weight loss is caused by the charge oxygen transformation into gas.

\[ R_i = \frac{\Delta O}{\Sigma O} \times 100 \ [\%] \]

where \( R_i \) - degree of (undirect) gas reduction

\( \Sigma O \) – total mass weight of oxygen bound to iron [g]

\( \Delta O \) – difference in mass weight of oxygen in ore during gas reduction [g]

Influence of reducibility on the blast furnace operation is highly important, it can be used for a fuel consumption determination and a selection of proper lumpiness. The reducibility value changes in particular by hot treatment (sintering). The charge porosity influences the
reducibility, too. The higher porosity of the charge, the larger reaction surface and the faster gas reduction.

The main parameter of a test in accordance with ISO- R ISO\(^950\) is the reduction velocity \(v_{40}\), which determines the velocity of oxygen degradation in \(\% \cdot \text{min}^{-1}\) at 40\% reduction degree.

\[
v_{40} = \left. \frac{dR}{dt} \right|_{\frac{Q_{0.9}}{Q_{0.5}}} \left( \frac{33.6}{t_{60}-t_{30}} \right) \text{(%min}^{-1})
\]

where:  
- \(t_{30}\) – time to reach 30 \% R (min)  
- \(t_{60}\) – time to reach 60 \% R (min)  
- 33.6 - constant

A static test for low-temperature reduction disintegration (RDI) evaluates the rate of agglomerate or ore resistance to grain disintegration during reduction in the upper regions of the blast furnace shaft. The principle of the method is in the reduction of 500 g of an iron ore sample with grains of 10 - 12.5 mm in a retort of the same dimensions as in R ISO\(^950\) test, but at 500 °C temperature and in a gas mixture CO + CO\(_2\) + N\(_2\) (20/20/60 \%). Reduction degradation index and strength index after \(R\) is obtained after spilling and assessment of grain proportions of + 6.3 mm, + 3.15, possibly 3.15 and below 0.5 mm.

Dynamic temperatures of the beginning and end of softening (\(t_1\), \(t_5\)) are defined by 1 \% and 5 \% deformation of a sample volume per a temperature increment of 10 °C. The dynamic temperature interval \(i_1 = (t_5 - t_1)\). Static softening temperatures (\(t_p\), \(t_k\)) are determined at 1 \% and 40 \% decrease in the initial height of the sample. The static temperature interval \(i_2 = (t_k - t_p)\). The data characterize thermoplastic properties of the raw ore.

**Coke**

*Coke chemical composition*

Ash is a constant part of each coke; it should not exceed 8 - 9 \%, moisture 4.5 \%, sulfur 1 \% and volatile substances 1 \%. On the contrary, a carbon content should be higher than 90 \%. Ash has an acidic character, which needs to be compensated by adding base additives.

The blast furnace coke quality is nowadays tested mainly by tests determining its strength characteristics and its reactivity.

The MICUM test determines cold strength properties of coke in the oxidation atmosphere. This evaluates coke stressing during sorting, storing, transporting to the blast furnace and staying in the upper region of the blast furnace. The MICUM test is performed in a steel drum of a diameter of 1 m and a length also of 1 m. The drum rotates around a continuous shaft and makes 25 rotations per minute. A sample of 50 kg weight is inserted into the drum and after four minutes, i.e. after 100 rotations, the coke is screened to fractions below 10 mm and above 40 mm. Follow-up, these fractions are weighed and the rest of coke lumps above 40 mm corresponds to the percentage value M 40, and the fraction below 10 mm refers to the value M 10. Blast furnace coke should have the M 40 value as high as possible, 65 \% and higher, while the M 10 value should not exceed 10 \%.

**CSR – CRI test** determining strength and reactivity of coke during the Boudouard reaction. 200 g of dried coke (\(m_1\)) with granularity of 19 -21 mm is weighed and this test sample is inserted into a retort. It is heated to 1100 °C temperature in the nitrogen atmosphere. The retort is blown through by CO\(_2\) for a period of 2 hours. Then the sample is cooled again the nitrogen atmosphere.

After the reaction tube cool-down, the sample is taken out and weighed. The generated metal scale need to be separated from the very gasified coke specimen. The weighed sample...
(m_2) is placed into a rotary drum and covered with a lid. After 600 rotations, the drum is stopped, the lid is opened and the sample taken out and screened on a 10 mm sieve. The coke fraction above 10 mm (m_3) is weighed and follow-up a calculation of coke strength and reactivity is performed.

\[
CRI = \frac{m_1 - m_2}{m_1} \times 100\% \\
CSR = \frac{m_3}{m_2} \times 100\% 
\]

Where: 
- m_1 - coke weight before the reaction in g
- m_2 - coke weight after the reaction in g
- m_3 - weight of the coke fraction of granularity > 10 mm after the drum test in g

The value of Coke Reactivity Index (CRI) should be lower than 35 % and of Coke Strength after Reaction (CSR) should be higher than 55 %. The presence of alkalis significantly increases the coke reactivity.

**Base additives**

The proportion of base additives in the blast furnace charge becomes more and more limited nowadays. If it is contained in the charge, it usually does not form an individual layer, but it is added to the charge together with the ore charge. Beside a requirement for a high content of free alkalis, for slag forming additives the accent is put on a proper granulometric composition. The granularity lower limit should not drop below 20 mm, so that the charge column permeability is not decreased. The additive grain size should not exceed 40 mm. For larger grains, dissociation occurs no sooner than in the bottom region of the furnace, in the high temperature area, which decreases the temperature, which should be as high as possible on this zone. At the same time, CO_2 from the dissociation reacts with the coke carbon (the Boudouard reaction), which is also strongly endothermic and decreases the coke grain diameter in the bottom region of the blast furnace. The voids content of the coke layer deteriorates and the blast furnace productivity decreases.

**Questions:**

1. What does the ore charge contain?
2. What are the functions of coke in the blast furnace?
3. How do base additives in the blast furnace act?
4. What is reducibility of raw ores?
5. What is granularity of base additives in the blast furnace and why?
6. What are the most important properties of raw ores and coke?
7. How is the blast furnace coke reactivity defined?
8. What are advantages of agglomerate in comparison with pellets?
9. Why must granularity of raw ores be higher than 6.3 mm?
3. CHARGING THE BLAST FURNACE

Subchapters:
- Transport of raw materials to the blast furnace top
- Function of the dumping system
- Main parts of the bell top
- A principle of the bell-less top
- Advantages of the bell-less top compared to the bell top
- Charging the material into the blast furnace

Lecture

Charging (dumping) is creating a charge column structure inside the blast furnace. The structure of particular materials affects most of the blast furnace processes: gas-dynamic permeability, contact of the solid charge and gas, heat exchange and the reduction process, a position and a shape of the cohesive zone, “dead man” characteristics and by this, through an influence on productivity, the specific consumption of coke, production quality and wear of furnace equipment, as well as the total cost-effectiveness of iron making. Research of dumping and application of the obtained findings are necessary to be evaluated as a system in the entire complex of knowledge on the blast furnace process.

Raw materials are transported to the blast furnace from storage bins. The particular raw materials are sorted prior to feeding into a skip car. Fine fractions are removed according to requirements for granularity. This is particularly important for the ore part of the charge, where grains below 6.3 (5) mm are to be removed.

The very distribution of the charge across the top is performed by the dumping equipment. The conventional bell top has been outdated nowadays, because the angle of the bell could not be changed and the material distribution across the top cross-section was performed mainly by control of size and order of individual charges. Today the bell tops are only used for the blast furnace production of low-phosphorus iron, where steel scrap needs to be charged into the blast furnace. An example of the bell top is shown in Figure 3.

Fig. 3 Mc Kee charging system with a rotating distributor of a Czech design
The purpose of dumping is to achieve a uniform flow of reduction gases across the cross-section as well as height of the blast furnace. The basic principle is that the fine grained charge (ore) is charged in where flowing needs to be suppressed, and the coarse grained charge (coke) is charged in where flowing needs to be supported. For this we need to know the actual distribution of gas streams (Chapter 6). The height of the charge surface is controlled today using microwave radiation based equipment. Radial distribution of gas streams is assessed on the basis of measurements of gas temperature and CO$_2$ content in 8 locations along the circumference and in the axis of the top above the charge surface. Where gas flows faster, higher temperature and lower CO$_2$ content is measured. Modern blast furnaces use horizontal insertion probes. The probe is inserted into the charge, under its surface and continuously measures temperature and composition of reduction gases from the furnace wall to its axis.

Increasing of the blast furnace useful volume (its dimensions) and the use of high pressure caused that bell tops, in spite of a considerable enhancement, were not able either to ensure an effective distribution of the particular charge components on the charge surface or to seal the inside of the blast furnace from atmosphere.

For these reasons a bell-less top was developed. The original design was worked out in Czechoslovakia (ing. Babinec patent, 1956). A principle lies in two material chambers, which are alternately connected with the inside furnace space or the charging equipment (movable hopper).

In the very furnace a discharge chute rotates, distributing material on the surface of the charge column in the radial direction. The chute has 2 rotating speeds, it can stop and charge on a point. It can have up to 24 possible angles of tilting. Actually, it can precisely control where the selected component of the charge is placed. A complicated problem is to interconnect all information on the actual existing profile of the charge surface and on distribution of gas streams with the bell-less top function. The bell-less top description is shown in Fig. 4.

Besides relatively perfect possibilities of dumping of blast furnace charge components on the charge surface and an effective sealing of the blast furnace, a great advantage is that repairs of the top can be done easier. A replacement or a repair of small lightweight components of the bell-less top can be performed during a common standstill of the furnace, while a replacement of a large bell or a dome needed a long-term furnace shut-down.
Fig. 4 Bell-less top description

Questions:

1. What is the function of the rotary hopper of the bell top?
2. Which parameters can be used to control charging across the cross-section of the blast furnace top?
3. What are disadvantages of bell tops?
4. What is the purpose of the material chambers of the bell-less top?
5. What is the movable hopper?
6. What are advantages of the bell-less top?
7. What equipment is used to measure the charge profile?
4. BLOWING BLAST TO THE BLAST FURNACE HEARTH

Subchapters:
- Hot blast stoves with the internal combustion shaft
- Hot blast stoves with the external combustion shaft
- Hot blast stoves without a combustion shaft
- Blast furnace tuyere systems
- Injection of gas, liquid and solid fuels into the blast furnace hearth
- Blast oxygen enrichment
- Pig iron quality management

Lecture

1.6 to 2.2 m³ of blast / 1 minute per each 1 m³ of the useful volume needs to be blown into the blast furnace (lower value refers to the oxygen enriched blast), i.e. 1400 m³. The blown blast always contains a specified amount of moisture (vapour), which reacts with fuel carbon, generating CO and H₂, so CO, CO₂, O₂, H₂, H₂O and N₂ occur inside the oxidation zone. On the boundary of the oxidation zone, oxygen and water vapour vanishes and CO₂ content drops rapidly. So in every place behind the oxidation zone boundary, only CO, H₂ and N₂ are contained in the gas.

Preparation of the blast furnace blast begins by air heating in blast stoves. Before that, cold air has to be compressed in the compressor station to the demanded pressure. Blast moisturizing is also performed prior to blast heating, because water vapour has three-atom molecules, which have a larger thermal capacity than two-atom ones. Thus the moisture increase in the heated air results in the enthalpy increase in the heated blast.

The very blast stoves are of a regenerative type, which means that in the first stage the heat accumulating chamber is heated by hot flue gasses generated in the combustion chamber by burning mixed gas with air. The mixed gas and combustion air is preheated by waste heat prior to the very burning. The blast stove is said to be on gas. In the second phase, the heat accumulating chamber, which has accumulated heat in the first phase, transfers the heat to the cold air and heats it to the demanded temperature. The hot blast is transported through the hot blast valve into the doughnut-shaped blast pipe and then it is directed into the furnace through nozzles called "tuyeres". The flow rate is regulated by the hot blast slide-valve.

At present, 4 hot blast stoves are used the most frequently. This arrangement enables to achieve sufficiently high temperatures and to minimize fluctuating. This allows trouble-less operation of hot blast stoves even at failure or repair of one stove.

Three concepts of hot blast stoves are used worldwide:
- Hot blast stoves with the internal combustion shaft
- Hot blast stoves with the external combustion shaft
- Hot blast stoves without a combustion shaft

Hot blast stoves with the internal combustion shaft
A scheme of the hot blast stove with the internal combustion shaft is shown in Fig. 5. Inside, at the steel casing on the left side of the stove, combustion shaft is placed. It can have a circular, half-circular, elliptical or oval cross-section. From the static point of view, the most preferable is the circular cross-section, however, it occupies the largest space and has the worst distribution of gas flows. In the bottom part of the shaft, there is a ceramic burner in which combustion occurs. Hot flue gasses rise to the dome, where they change the flowing direction and heat the checker-work while flowing through the passages. The dome is one of the critical regions, where the maximum temperature must be controlled.

An advantage of placing the combustion shaft inside the very stove are less thermal losses to the environment. Due to uneven thermal stressing, the combustion shaft is the most stressed element.

- Inside the shaft, temperature along the height is approximately the same, but on the checker-work side the temperature decreases in the direction from the dome towards the grate.
- The shaft lining temperature on the checker-work side is different from that at the circumferential brickwork, it has a different thermal dilatation. The temperature changes along with the place and time.
- The shaft wall temperature in the combustion space is higher than on the checker-work side. The hot side has a larger thermal growth than the cold side and the wall tends to incline to the cooler side.
- Bending of the combustion shaft and cracking of the brickwork increase along with the blast stove size and the combustion shaft length.

The dome is set on the stove casing, so that the circumferential brickwork can dilate freely (off-set dome).

**Hot blast stoves with the external combustion shaft**

Troubles with brickwork damages in stoves with the internal combustion shaft have led to dividing the stove to two parts, a separate shaft and a container with the checker-work. Both the containers are connected by the connecting dome (Fig. 6). There are three basic conceptions, which differ just by the connecting dome. Thermal dilatation between containers is compensated using compensators. In comparison with hot blast stoves with the internal shaft, there are not so much troubles with brickwork, they have better gas flowing distribution, however, they have higher thermal losses.

**Hot blast stoves without a combustion shaft**

Hot blast stoves without a combustion shaft are the newest, the most perspective solution for blast heating. A principle is an arrangement of the combustion chamber in the dome above the checker-work. There are the following types:

- Blast heating with burners arranged along the dome circumference
- Blast heating with tangential burners
- Blast heating with a ceramic burner in the stove axis

Advantages of blast heating without the combustion shaft

- Better utilization of the layout
- Less surface of the stove
- Lower weight of the casing and lining
- Higher heating efficiency

From hot blast stoves the blast is directed through the bricked pipeline into the doughnut-shaped blast pipe that encircles the furnace belly. The regulation valves must be cooled. From the doughnut-shaped blast pipe the gas is directed through a branch line to each tuyere. The tuyere system is shown in Fig. 7.
Fig. 5 Scheme of the hot blast stove with the internal combustion shaft
Fig. 6 Hot blast stove with the external combustion shaft

Fig. 7 Tuyere system with flexible attaching to the shell
The main tuyere leading into the furnace is made of copper and is water cooled intensively. A protective tuyere and a cooling box follow. Blast is directed into the tuyere through a blast nozzle (belly pipe); a boot leg, distance piece, branch and doughnut-shaped pipe follows. The tuyere system is attached flexibly to the blast furnace shell to enable to compensate thermal dilatations. In new type tuyere systems, thermal dilatations are compensated using compensators (Fig. 8).

![Fig. 8 Tuyere system with compensators](image)

Figs. 9 – 10 show various designs of copper tuyeres.

![Fig. 9 Examples of tuyere designs](image)

![Fig. 10 Photo of a tuyere cross-cut](image)
Injection of gas, liquid and solid fuels into the blast furnace hearth

Blast furnace coke becomes more and more expensive and deficit fuel, because production of pig iron does not decrease and worldwide reserves of coking types of coal run low rapidly. One of the ways leading to reduction of the coke specific consumption is injection of substitute fuels into the blast furnace hearth along with blown blast. These are above all: - Natural gas - Coke gas - Heavy oils - Pulverized coal

Natural gas

Natural gas is a traditional substitute fuel used just since the half of the last century. It is transported to the metallurgical plant under high pressure, which is only reduced to the demanded value for injecting into the blast furnace hearth. Natural gas is without impurities and there are no handling problems. It has the highest cooling effect and allows high oxygen enrichment of blast. Its only disadvantage is a high price. In the first phase, it decomposes in the blast furnace and the endothermic effect of this decomposition is a base for its cooling effect.

\[ \text{CH}_4 = \text{C} + 2\text{H}_2 \]

In the second phase, the generated carbon is oxidized by oxygen to CO. This reaction is exothermic, exactly like coke carbon burning. A fact that natural gas is injected at ambient temperature, while coke enters the oxidation region preheated to c. 1500 °C, contributes to the temperature decrease, too. This principle applies for all hydrocarbon fuels.

Coke oven gas

As a blast furnace plant usually incorporates also a coke plant, its use for injecting to the blast furnace seems to be preferable. However, in operation it is used only in few cases for the following reasons:

- Coke oven gas has low pressure and a compression station needs to be built for its use
- The main heating component of coke oven gas is hydrogen. As dissociation does not occur upon its injection, it has not a cooling effect and does not allow high oxygen enrichment of blast and intensification of production
- In spite of its cleaning, it contains condensed hydrocarbons (naphthalene), clogging distribution valves

Heavy oils

The first successful operational experiments with the use of mazout as a substitute for the blast furnace coke were performed in the 50s of the last century already. Nowadays this technology has been placed aside, because the world price of crude oil, from which these heavy oils are extracted, has arisen considerably.

Heavy oils as mixtures of heavy hydrocarbons require for their pyrolysis to carbon and hydrogen only about one third of heat in comparison with natural gas, therefore their injection into the blast furnace hearth is connected with a less decrease in the theoretical temperature in oxidation zone. Also a growth of the amount of gas combustion products per one oil mass unit at its imperfect burning is lower than at natural gas burning, and this means lower demands for the blown blast temperature increase or for a degree of its oxygen enrichment. With each percent of additional oxygen the furnace productivity increases by 2.3 – 5.6 % and the coke specific consumption decreases. However, this coke consumption decrease, similarly as with
injection of natural gas, relates above all to the coke substitution by oil. A coefficient of coke substitution by heavy oils fluctuates within a wide range from 0.9 to 1.5 kg kg\(^{-1}\) and decreases dramatically, while the injected oil amount increases.

Elimination of blown blast moisturizing and increasing its temperature is usually enough to equalize the burning temperature at low oil consumption to c. 30 kg t\(^{-1}\) of pig iron. At consumption of 45 to 65 kg t\(^{-1}\), blast needs to be enriched to 22 to 23.5 % of O\(_2\). Every other increase in the oil specific consumption requires a higher concentration of oxygen in blast and for instance when injecting 100 kg of oil per 1 t of pig iron, blast enrichment to less than 26 vol.% of O\(_2\) is not sufficient. At these high specific consumptions of oil, considerable technological problems occur in the blast furnace operation, because all oil is not gasified in the oxidation zones and furnace black forms, disturbing a fluent run of the blast furnace and making top gas cleaning difficult. The furnace black formation can be in this case prevented by using the so-called oil emulsifiers, which contribute to a fine dispersing of the oil stream after its outlet from nozzles.

Oil is transported to the plant in tanks and conveyed to the blast furnace via special pipelines and pumps. In order to keep the oil viscosity adequately low, tanks are steam heated to 70 to 80 °C and electric heaters are installed by the oil outlet, increasing the transported oil temperature to 10 - 130 °C. The oil is filtered before the inlet into the circular oil pipeline at the blast furnace and then distributed to the individual tuyeres through branches fitted with control valves. The very nozzles are made of stainless steel and usually operate on the injection principle. Compressed air serves both for injection of oil and for its fine dispersing. At the same time, it also prevents nozzle clogging. Water steam is used for cleaning the entire system (Fig. 11).

![Fig. 11 General scheme of the system for oil injection into the hearth](image)

1 – flowmeter, 2 - control valve, 3 – flexible copper hose with a steel sheath, 4 – quick-exchange flange, 5 – nozzle, 6 – air reservoir (0.5 – 0.6 MPa)
a – nozzle detail

Particular designs may vary considerably. Nozzles are typically directed obliquely downwards to achieve as long path of oil drops in oxidation zone as possible. Therefore even tuyeres with oblique front ends are often used.
In many plants, blast furnaces are equipped with injecting systems both for natural gas and heavy oils, which enables to react flexibly to an offer of individual types of additional fuels in various seasons of a year. Despite the fact that heavy oils typically contain considerable amount of sulfur (some kinds as high as 3.5%), the sulfur content in pig iron is usually not increased. This can be explained by a more fluent run of the blast furnace and a possibility to maintain higher basicity of slag.

Nowadays a part of heavy oils is substituted by tar. Either black coal tar from coke plants is used, into which foul solvents, waste oils etc. can be added, or brown coal tar, formed during gasification of lignite. While black coal tar needs to be heated prior to injecting, brown coal tar has a satisfactory viscosity even at normal temperature. However, brown coal tar must not be mixed either with black coal tar, or with oils (no transport through the same piping), because asphaltenes disabling its transport (pipe clogging) are formed. When conveyed, brown coal tar must not get into a contact either with rubber or bronze components, which requires a special pump design.

**Pulverized coal**

Due to the deficit of heavy oils and in particular as a result of their price growth, recently the interest has been focused on substituting a part of metallurgical coke by pulverized coal injected into the blast furnace hearth similarly as gas or liquid fuels.

A low price of pulverized coal injection into the blast furnace hearth is its great advantage compared to other substitute fuels. As a result of inevitable dissociation of hydrocarbons contained in coal and missing heat of preheating of the substituted part of metallurgical coke the burning temperature in the hearth decreases as well, however, less dramatically, because this dissociation heat is low. The pulverized coal burning thermal effect in the blast furnace oxidation region, and thus also the coke substitution coefficient, depends above all on carbon content in injected coal and this can be highly different. When injecting black coals with a high proportion of involatile carbon, the coke substitution coefficient can be up to 1 kg kg\(^{-1}\), for brown coals it is 0.45 to 0.55 kg kg\(^{-1}\).

Since the hydrogen content in coal is low, in contrast to gas or liquid fuels, its effect on reduction activity of the gaseous phase is limited. The higher ash content in coal has also an adverse effect, because the specific amount of slag increases, and an adverse effect of an increased sulfur content on pig iron quality is important, too. Therefore for this purpose usually non-coking types of coal with low ash and sulfur contents are chosen.

In all systems for injection of pulverized coal to the hearth, high attention is paid to fine milling of coal and eveness of its transfer to the particular oxidation zones of the blast furnace depending on the blown blast amount. Optimal coal granularity is less than 0.1 mm and as its transport is performed pneumatically, a low moisture content is important as well (typically <4%).

Complexity of the pulverized coal injection system consists not only in a need for drying and fine milling of coal, but also a need to transport the milled coal using an inert gas. The use of nitrogen is perfectly safe, however, the blast furnace gas reducing capacity is rather
decreased. By injecting black coal and particularly coke dust, the transport pipelines suffer very much and need to be replaced after a relatively short time (about 1 year). When injecting brown coal, these problems are reduced.

At present, injection of up to 200 kg of coal per ton of produced pig iron is reached. The total flow volume of pulverized coal injected into the blast furnace should be evenly distributed into the individual injection pipelines and injection nozzles using a separator (distributor). An even distribution of the total flow volume of pulverized coal to each tuyere needs to be achieved. The coal is transported into the tuyeres through one or two pipes.

Fig. 13 Scheme of the pulverized coal injection system


**Blast oxygen enrichment**

Atmospheric air compressed by air blowers contains about 20.85 % of oxygen. By increasing oxygen concentration in the blown blast the proportion of the led-in nitrogen decreases, thus increasing burning temperature and rate. Along with a decrease in the gas volume the kinetic energy value decreases, however, this decrease can be limited to a certain extent by a temperature increase in the oxidation region. However, this temperature increase is quite low, because at lower amount of gas, the conditions for heat transfer improve and pig iron and slag absorb the most of the excess heat. If along with the blast oxygen enrichment the blown blast amount increases, oxidation regions can remain unchanged, possibly can enlarge.

At the oxygen enrichment of blast, the blast furnace productivity generally increases, because the gas amount per a unit of production decreases. However, at the same time
temperature in the oxidation zones increases markedly, therefore the additional heat consumption in the hearth needs to be ensured to compensate the temperature increase. This condition is met by a high degree of direct reduction, e.g. in production of foundry iron and above all ferromanganese and ferrosilicon or injection of hydrocarbon fuels, which consume a high amount of heat for their dissociation. Blast moisturizing would meet this condition, too, however, at the cost of the increased specific consumption of coke.

When making pig iron for steel plants without hydrocarbon fuels injection, blast can be enriched to max. 22 – 23 vol. % of O\textsubscript{2}. At higher oxygen concentrations, the phenomenon called ‘hanging’ of charge occurs, leading to impaired run of the blast furnace. A probable cause is an increase in a proportion of gasified and condensed silicon monoxide and also a decrease in size of the oxidation zone. This adverse effect can be eliminated, possibly even removed, not only by a faultless preparation of charge and using high quality coke, but also by every measure resulting in temperature decrease in oxidation zones, e.g. by blown blast moisturizing, injection of substitute fuels, limestone, pulverized ores and also by increasing slag basicity and deterioration of its fusibility (Al\textsubscript{2}O\textsubscript{3} content increase). For foundry iron production, about 27 vol.% of oxygen in blast is advisable; the increased cost for oxygen production is compensated by achieved savings in the blast furnace production. Oxygen enrichment of blast in the production of blast furnace ferroalloys is usually cost-effective even at considerably high oxygen concentrations. The reason is that both the heat excess in the hearth is consumed for direct reduction of elements with low reducibility and heat losses reduce due to noticeable decrease in top gas temperature. The furnace enhanced productivity is also caused partly due to a reduced gas amount per a production unit at relatively high permeability of the charge column as a result of a high coke/ore ratio.

As by oxygen use the oxidation regions decrease in size, there are conditions for more intensive gas flowing along the furnace circumference. Therefore a proper adaptation of the furnace filling procedure is needed.

Completely different are conditions for injection of hydrocarbon fuels (natural gas, heavy oils etc.) into the hearth, when the blast oxygen enrichment is useful and at high proportions of these fuels even necessary.

For blast furnace purposes, oxygen is not typically of high purity, because it is mixed with air. Oxygen of 75 – 80%, the production of which is cheaper, is sufficient.

**Theoretical burning temperature**

The highest temperature of gas in the oxidation region, reaching to 1900 – 2200 °C, is in places where the highest CO\textsubscript{2} concentration is, which is a result of composition and temperature of blast. The lowest gas temperature is in places where CO\textsubscript{2} disappears; this is usually on the boundary of the oxidation region, which is a result of the endothermic Boudouard reaction. The theoretical temperature on the oxidation region boundary can be expressed as:

\[ t_{\text{teor.}} = \frac{Q_{\text{CK}} + Q_{\text{EK}} + Q_{\text{EV}} + Q_{\text{DH2O}} + Q_{\text{NP}} + Q_{\text{ENP}} - Q_{\text{DNP}} - Q_{\text{DH2O}}}{V_{N_2} \cdot c_p \cdot N_2 + V_{CO} \cdot c_p \cdot CO + V_{H_2} \cdot c_p \cdot H_2} \text{ [°C]} \]

where:
- \( Q_{\text{CK}} \) - heat of the incomplete coke carbon burning [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{EK}} \) - coke carbon enthalpy [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{EV}} \) - blown blast enthalpy [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{DH2O}} \) - dissociation heat of blast moisture [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{NP}} \) - heat generated by substitute fuels [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{ENP}} \) - substitute fuels enthalpy [kJ.kg\textsuperscript{-1}]
- \( Q_{\text{DNP}} \) - dissociation heat from substitute fuels [kJ.kg\textsuperscript{-1}]
V\textsubscript{N2}, V\textsubscript{CO}, V\textsubscript{H2} - volume amount of hydrogen, CO and nitrogen in flue gasses [m\textsuperscript{3}. kg\textsuperscript{-1}]
C\textsubscript{pH2}, C\textsubscript{pCO}, C\textsubscript{pN2} - mean specific heat of hydrogen, CO and nitrogen [kJ. m\textsuperscript{-3}.K\textsuperscript{-1}]

The above mentioned formula implies that the temperature in the oxidation region increases along with fuel calorific power, with a degree of coke preheating, blown blast and substitute fuels. On the contrary, the theoretical temperature decreases with the increased blast moisture value, dissociation heat of substitute fuels and an increase in gaseous waste products.

During passing of the coke through the blast furnace, the coke is heated to temperature near 1500 °C, at the mean specific heat of coke about 1.67 kJ. kg\textsuperscript{-1}. K\textsuperscript{-1} is a value Q\textsubscript{CK} 2345 to 2512 kJ. kg\textsuperscript{-1}. Dissociation heat of water vapour is 10802 kJ. m\textsuperscript{-3}. Out of substitute fuels, the highest dissociation heat has natural gas, about 3182 kj. m\textsuperscript{-3}, while heavy oils consume 1465 to 1591 kJ.kg\textsuperscript{-1} for their dissociation. This consumption increases along with the increasing ratio \( \frac{H}{C} \) in fuel.

**Pig iron quality management**

Quality of the produced pig iron can be defined by its chemical composition and temperature. As various elements are reduced and dissolved in liquid iron at different temperatures, their content in hot metal depends on temperature in the blast furnace hearth. The basic temperature-thermal level in the hearth is on a long-term basis determined by the blast furnace charge composition, mainly amount and quality of blast furnace coke. The liquid iron temperature control through temperature control in the blast furnace oxidation zones is more operational. As the hearth pad and walls are thermally isolated and cooled, the liquid iron and slag temperature can be controlled just by directing heat from the oxidation zones through the slag layer. The above mentioned formula for the calculation of the burning theoretical temperature enables to define interventions for increasing and decreasing the temperature before the tuyeres and the hearth. Temperature in the hearth can be effectively controlled by control of intensity of substitute fuels injection and blast enrichment with oxygen. Regulation of blast temperature and moisture is also used for the control.

**Questions:**

1. What is a composition, temperature and speed of the blast furnace blast?
2. What types of hot blast stoves do you know?
3. Compare advantages and disadvantages of the blast stove with the internal and external combustion shaft?
4. Why hydrocarbon substitute fuels decrease TTH?
5. Why blast enrichment with oxygen increases TTH?
6. What are disadvantages of coke gas injection into the blast furnace hearth?
7. What are advantages of pulverized coal injection into the blast furnace hearth?
8. How can silicon content in pig iron be increased?
5. CONTROL OF CHARGE AND GAS COUNTER-CURRENT AND MANAGEMENT OF BLAST FURNACE PRODUCTIVITY

Subchapters:

- Gas pressure drop in the grain layer
- Influence of the gaseous phase composition and properties on the pressure drop
- Influence of charge raw materials composition and properties on the gas pressure drop
- Possibilities of gas flow control in the blast furnace
- Peripheral, central and regular run of the blast furnace
- Management of the blast furnace productivity
- High pressure method
- Technology of blast enrichment with oxygen

Lecture

The blast furnace is a counter-current reactor where solid charge descends and reduction gases ascend continuously. This means that forces affecting the charge particles in the downward direction must be higher than forces acting against the charge descend – the gas kinetic energy, friction forces and buoyant force of coke immersed in pig iron and slag.

\[
G > V
\]

\[
G = \rho_m \cdot g \cdot h \\
V = 0.5 \cdot \rho_g \cdot w_g^2 + T + A
\]

Fig. 14 Condition of the blast furnace operation
\( \rho_m \) – charge grain density
\( \rho_g \) – gas density
\( g \) – gravity acceleration
\( w \) – gas velocity
\( T \) – friction forces
\( h \) – distance from the level of dumping and pig iron

The gas kinetic energy, i.e. the velocity of flowing reduction gases, has a decisive role. The grain charge ability to let the gaseous phase through is usually evaluated by its permeability. As the blast furnace charge permeability cannot be continuously monitored with satisfactory accuracy, this parameter is typically replaced by a value of gas pressure drop in a defined height.

The gas pressure drop in the grain layer is usually calculated using the so-called Ergun equation:

\[
\Delta P = \xi \cdot \frac{1 - \varepsilon}{\varepsilon^2} \cdot \frac{\Delta h \cdot \rho_0 \cdot \omega_0^2}{d \cdot \Phi} \cdot \frac{T}{T_0} \cdot \frac{P_0}{P}
\]

where:
- \( \Delta P \) – the gas pressure drop in the grain layer (Pa)
- \( \xi \) – aerodynamic resistance coefficient (1)
- \( \varepsilon \) – voids content in the layer (m\(^3\). m\(^{-3}\))
- \( \Delta h \) – evaluated column height (m)
- \( d \) – mean linear dimension of grains (m)
- \( \Phi \) – grain shape coefficient (1)
- \( \rho_0 \) – gas density (kg.m\(^{-3}\))
- \( w_0^2 \) – gas flow velocity (m.s\(^{-1}\))
- \( T \) – real gas temperature (K)
- \( T_0 \) – standard gas temperature (K)
- \( P \) – real pressure (Pa)
- \( P_0 \) – standard pressure (Pa)

To be able to calculate the pressure drop in the grain layer, we need to know values of the above mentioned quantities, possibly to calculate them from the available values.

As in various distances from the blast furnace axis the granulometric composition of the charge varies (coke to ore ratio), there is a different voids content there, and also a different flow velocity of blast furnace reduction gases. A result is a different velocity of the solid charge descending in a different distance in the radial direction. Then the furnace charge descends in the radial direction unevenly. From the technological point of view, this unevenness should be purposeful and controlled.

Considering this unevenness, there are three types of blast furnace “run”.

The inner (central) run of the blast furnace is such an operation, where gas flows and charge descends mainly along the furnace axis. The charge descend by the furnace walls is slow.

The outer (peripheral) run of the blast furnace is such an operation, where gas flows and charge descends mainly by the furnace walls and only a little in the central region of the furnace.

The regular run of the blast furnace is a compromise between the mentioned furnace operations; the gas flowing is distributed rationally along the radial cross-section of the furnace.

The gas flows distribution in the furnace assumes the knowledge of their distribution. The gas temperature and composition along the furnace axis and in the individual octants along the circumference (at the furnace wall) are measured at the blast furnace top.
The hearth gas exiting the oxidation zones has a high temperature (as high as 2000°C) and contains carbon in CO form (no CO₂). In places where gas flows quickly, it has not time enough to cool down and CO has not time enough to be reduced to CO₂.

Gas flowing is usually controlled from the top (by dumping). A permeable charge (coke) is dumped to places where gas flowing needs to be supported. A non-permeable finer charge (ore) is dumped to places where gas flowing needs to be suppressed. Control parameters include also the charge size, the order of particular components of the charge etc. The bell-less top provides substantially better conditions for gas flowing control in the blast furnace than the bell top. Gas flows can be also controlled from the bottom through blast parameters.

Management of the blast furnace productivity

Continuous descending of the charge and flowing of reduction gases is a condition for the blast furnace run. The faster the charge descending, the higher the blast furnace productivity. An essential principle for increasing the furnace productivity is an increase of the blown blast amount. Due to increasing the blast amount more coke can be burnt, more heat and more reduction gas are generated and due to burning a higher coke amount a larger area is cleared for the charge descend. By farther increasing of the blown blast amount, a rate of the productivity increase decreases, until stopping of charge may occur. Along with increasing the blast amount the velocity of its flowing increases, which, as shown in Fig. 14, increases the force acting against the charge descend. Decreasing the gas flow velocity through the charge is necessary for further productivity growth. All actions leading to a decrease in the gas flow velocity lead to the productivity increase.

In practice, two basic methods are used to enhance the productivity.

1. **High pressure method**
   The method is based on choking a gas outlet from the blast furnace using a choking system, the so-called expander. The pressure of gas in the blast furnace shaft increases, its volume decreases, leading to a decrease in the gas flowing velocity in m.s⁻¹ or in m³.s⁻¹. Velocity in g.s⁻¹ or in mol.s⁻¹ remains the same. The gas density increases. The gas velocity decrease reduces the force acting against descending of the charge and accelerates the charge descend.

2. **Technology of blast enrichment with oxygen**
   Increasing the oxygen content in the blast at the same amount of burnt coke decreases the nitrogen proportion in the blast and also in the reduction gas, resulting in a decrease in the gas amount and thus also the flowing velocity. The consequences are the same as with the first method.

   A certain possibility how to increase productivity is also an increase in the charge weight, for example by replacing agglomerate with pellets. Pellets have a higher iron content (they are heavier) and higher bulk density (ideal grain shape).

---

**Questions:**
1. What is a condition for the charge descend in the blast furnace?
2. What forces act on the charge grains in the direction downwards and upwards?
3. What is a pressure drop in the grain layer?
4. How do the charge granularity and voids content influence the pressure drop?
5. How does the type of gas flowing (turbulence) influence the pressure drop?
6. Do grain shapes influence the charge permeability?
7. Why hydrocarbon substitute fuels decrease TTH?
8. What is the principle of the technology of high pressure at the top?
9. What is the principle of the technology of blast enrichment with oxygen?
10. How does an increase of the blast amount influence the blast furnace productivity?
6. CASTING THE LIQUID PRODUCTS AND THEIR PROCESSING

Subchapters:
- Tapholes for liquid products
- Blast furnace casthouse
- Blast furnace casthouse equipment
- Casting the liquid iron and slag
- Transport of the liquid iron and slag
- Casting equipment
- Granulation of slag
- Ladle desulphurization of pig iron

Lecture

A number of liquid iron tapholes depends above all on the blast furnace size and operation intensity. When decreasing the slag specific amount to 300 – 350 kg/t of liquid iron, the slag tapholes lose their significance, because the top slag is actually not drained. The liquid iron tapholes are situated in the bottom part of the hearth wall as openings of a rectangular cross-section of a width 250 – 300 mm and a height 450 – 500 mm. The furnace shell in the taphole area is enclosed with a steel frame and its inner surface is lined with the first grade chamotte. This area can have a rectangular or oval shape and its relatively high height enables to change the position of the very tapping hole in the refractory clay plug, which fill the whole area of the taphole. Vertical coolers of the hearth with the own cooling are connected to the frame.

Liquid iron and slag flow through the tapholes down out of the furnace, to the casthouse. The casthouse arrangement depends on a local layout.

The very liquid iron tapping is carried out by drilling or punching using a taphole drill, which is a part of the casthouse equipment. At present, the blast furnace slag is tapped along with liquid iron and is separated in the trough.

![Fig. 15 Scheme of casting the liquid iron and slag](image)

Blast furnace slag processing
Blast furnace slag is a by-product of the pig iron production and nowadays the whole amount is used mainly in building industry.

The largest proportion of the blast furnace slag is used for production of cement. This slag is processed at blast furnaces through the so-called granulation. Using water, the liquid slag is rapidly cooled and sprayed. For production of cement the slag is needed to be solidified amorphously, as glass, not to have crystalline structure (90 % amorphous structure at minimum).

On the contrary, the slag, which is used in the building industry as slag aggregate, should have as perfect crystalline structure as possible in order to have adequate strength. Slag is poured into slag pits, where it is kept to crystallize slowly. The slag after crystallization should not contain a mineral “larnite” (dicalcium silicate - 2CaO.SiO₂), which recrystallizes during cooling (500-600 °C), its lattice increases the volume by 10 % at transformation from β phase to γ, resulting in disintegration of slag lumps. The blast furnace slag is used for the manufacture of isolation materials.

**Ladle desulphurization of pig iron**

Although desulphurization in the blast furnace is much more effective than in the steel plant, sulfur content reduction requires increasing the liquid iron temperature and the slag basicity. However, this leads to the coke specific consumption growth and an increase in pig iron production cost. If there is a need to reduce sulfur content in pig iron below 0.01 %, an installation of the ladle desulphurization equipment usually pays off. Savings in the blast furnace operation due to the iron temperature decrease and elimination of base additives in the charge should be higher than the cost for the ladle desulphurization. A higher price of the manufactured steel is also a benefit.

The ladle desulphurization is performed in a vessel into which desulfurizing agents in powder form based on CaO, MgO, Mg, Al etc. are injected through an immersion lance. Their amount and composition vary along with time. A scheme of the ladle desulphurization is shown in Fig. 16.

![Fig. 16 Scheme of ladle desulphurization of pig iron](image)
Questions:

Why the slag taphole has not been used anymore?

1. Where is the blast furnace slag separated from the liquid iron?
2. What is the purpose of the casting equipment?
3. What is the purpose of the slag granulation?
4. Which mineral causes disintegration of slags?
5. When is the ladle desulphurization of liquid iron used?
7. TOP GAS CLEANING

Subchapters:
- Preliminary cleaning of the blast furnace gas
- Semi-fine cleaning of the blast furnace gas
- Fine cleaning of the blast furnace gas
- Equipment for pressure increasing in the blast furnace
- General flowchart of the blast furnace gas cleaning

Lecture

A method and a rate of utilization of the top gas is nowadays one of indicators of advancement in a metallurgical plant. Although the top gas calorific value is low, considering its large amount it is a significant part of an energy balance in a company.

To enhance the design and to increase the efficiency of devices consuming the top gas demands higher requirements for the top gas cleanliness. In the blast furnace plant, this relates also to operating life of hot blast stoves, valves, fixtures and piping. The coke-oven battery heating system requires gas cleanliness below 5 mg.m⁻³.

Blast furnace gas properties

The top gas is a by-product generated from processes running in the blast furnace during liquid iron production. It is a flammable, explosive and toxic gas. The main flammable and toxic component is CO. Hydrogen and methane take their part in the calorific power.

Composition of the top gas:

<table>
<thead>
<tr>
<th>Component</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>22 – 28 %</td>
</tr>
<tr>
<td>CO₂</td>
<td>14 - 20 %</td>
</tr>
<tr>
<td>CO + CO₂</td>
<td>38-42 %</td>
</tr>
<tr>
<td>H₂</td>
<td>2 – 4 %</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.3 – 0.8 %</td>
</tr>
<tr>
<td>N₂</td>
<td>53-57 %</td>
</tr>
</tbody>
</table>

The gas composition depends on many factors, mainly on the fuel amount in the charge and on the technology of the blast furnace control.

The top gas calorific value depends on its composition, it is about 4 MJ.m⁻³.

Explosive limit: lower – 30 %, upper – 70 %. Besides the calorific value, the dust content is also a criterion for the blast furnace gas usability.

Exit of the gas from the top

The top gas flows from the top through four and follow-up through two vertical gas ducts, the so-called ascending pipes. It contains, according to operational conditions, 2 up to 60 grams of particulate matter in 1 m³ of the gas. The exhaust pipes are placed on the top circumference and positioned by 90° towards each other. A properly chosen diameter, typically 2000 mm, has to enable to reduce the flow rate, as well as the gas duct vertical height has to reduce the amount of the throat dust by enabling its back fall into the blast furnace. The gas velocity in these places has not to be higher than 10 m.s⁻¹. The gas volume, as well as its velocity, is substantially influenced by its temperature.

The throat dust amount from the blast furnace is affected mainly by the following factors:
- The charge physical properties
- Proper technology of the blast furnace operation
• The blast furnace thermal regime
• The amount of the blown blast
• Pressure in the blast furnace top
• The method of the blast furnace charging
• The design of the top and the top equipment

The blast furnace throat dust consists of particles of ore charge, coke and base additives captivated and carried by the flowing gas. The throat dust granularity ranges from 1 μm to 500 μm. While the particle dimensions decrease, their specific surface quickly increases. Along with the increase in surface, the ability to absorb gas increases as well, grain wettability deteriorates, which makes capture of grains by a washing liquid more difficult. For example, a surface of 10 mg of particles of granularity 500 μm is 0.428 cm², of granularity 0.1 μm is 2140 cm². The large range of granularities requires gas cleaning in several steps. The Newton law can be used for particulate matter of granularity above 10 μm, particles below 10 μm do not adhere to this law and particles below 0.1 μm are not governed by laws of mechanics of solid materials and behave in a completely different way.

The top gas cleaning can be divided to:
- Preliminary gas cleaning
- Semi-fine gas cleaning
- Fine gas cleaning

**Preliminary cleaning of the top gas**

The preliminary cleaning of the top gas is carried out through a dry process in dust catchers or cyclone separators. Gravitational and centrifugal forces are used in this process. Dust catchers with an axial inlet of gas are used in the Czech Republic (Fig. 17). The limiting velocity of gas flowing must be lower than the critical velocity, which can be calculated from the equality of forces of atmosphere resistance and a force from the grain weight. Also, cyclone separators are used abroad, where the centrifugal force is used, increasing the dust separation efficiency.

![Dust catcher with an axial inlet of gas](image)

**Fig. 17. Dust catcher with an axial inlet of gas**

**Semi-fine cleaning of the top gas**

At present, water washers (scrubbers) are used for semi-fine gas cleaning the most frequently. These are steel vessels of a cylindrical shape. Water spray nozzles are arranged on
several horizontal levels, so that a thick water screen can be created across the whole horizontal cross-section (Fig. 18). Water wets the surfaces of particles and removes them away in a form of sediments, which are drained off from the bottom part of the scrubber. In operation, low-pressure scrubbers with a wood bed and high-pressure scrubbers without any bed are used. The high-pressure scrubbers have a significantly lower pressure drop and higher efficiency (as high as 96 %).

The dust separation efficiency in scrubbers depends on:
- Dust wettability
- Gas flow velocity
- Washing water to gas amount ratio
- Surface stress of the liquid
- Atomization of water (nozzle design)
- Water and gas pressure
- Dust content in the gas
- Granulometric composition of dust

**Fine cleaning of the top gas**

At present, the following devices are used for fine gas cleaning:
- Electrostatic dust separators (electrofilters)
- Fabric filters
- Venturi jet washers

In the Czech Republic, at present, the most widely used method of fine cleaning of the top gas is used – the Venturi jet washers.

The principle of cleaning comes out of the knowledge that larger particles are easier to separate and it is advantageous to coagulate fine dust particles together to become larger and heavier.

In Venturi turbulent washers, the coagulation of particles is achieved; dust containing gas impinges at a high velocity (up to 300 m.s\(^{-1}\)) the water screen formed by jets of different designs in the narrowest place (throat) of the device. Wetting and coagulation of particles occur. Atomizing of water into a fog of tiny droplets is not achieved only by the water pressure (0.3 – 0.4 MPa), but also by the impact of the moving gas on water droplets. A size of water droplets is less than in scrubbers.

Atomization of water has two basic causes:

a. Primary atomization of water as a result of a high difference in the velocity of water droplets and the gas stream

b. Secondary atomization caused by rotation – disintegration in the turbulent stream

The first phase of the process is a capture of water droplets in the gas stream. In order to make advantage of the maximal difference in water and gas velocities, the place of injection has to be positioned as close to the washer throat as possible. At the same time, an even distribution of water along the gas stream cross-section is needed.

The second phase is evaporation and condensation of water in gas. Vapour contained in the gas can condense as a result of pressure and temperature decrease. This occurs mainly on the surface of tiny particles, which have a lower temperature than the condensation point temperature. If the gas was not saturated with water vapour, evaporation of tiny water droplets occurs simultaneously.

c. Coagulation of sludge particles and their capturing

Larger dust particles, due to their mass, break through the water droplet surface stress barrier and are absorbed and separated by the droplet. Particles less than 0.1 μm cannot be captured
inertially and their capture is explained by diffusion. Fine particles behave as large molecules – they diffuse to water droplets; this requires time. This process demands low velocities $50 – 60 \text{ ms}^{-1}$.

The method and the place of water injection have the biggest influence on the washer design. According to this, the Venturi-type washers are divided to washers with:

- Central sprinkle watering (in the axis of the jet)
- Circumferential sprinkle watering (perpendicular to the axis of the jet)
- Membrane sprinkle watering
- Contactless sprinkle watering (from the level)

![Fig. 18 Water washer (scrubber) for the blast furnace gas](image)

**Adjustable throat Venturi-type washers**

This type of gas cleaning belongs among the most effective methods of gas cleaning. In the principle of such a process of separating solid, liquid and gaseous substances, there is no lower limit considering grain sizes or their concentration. In each wet separating, it is possible to catch even the finest particles by increasing the inertia force at the corresponding high velocity of gas. During development of the washer with a circular throat the aim was to obtain markedly turbulent flow in the boundary layer, with a large amount of small turbulences, being the most suitable for transport processes as a result of intensive stirring. The washer with the circular throat has an axially symmetrical design. This allows achieving a uniform water distribution across the whole round cross-section of the throat using the screw jet,
which operates without clogging. The washers with a circular throat are made in the following variants:

- The circular cross-section converging in the flow direction
- The circular cross-section diverging in the flow direction
- The washer with a circular throat as a water seal
- The washer with a circular screw throat
- The washer with a special outlet for high differential pressures

Selected types are shown in Fig. 19.

The washer with a circular throat has a function of cleaner as well as a gas flow rate controller. This method of gas cleaning allows cleaning to values below 1 mg.m\(^3\) of gas.

Behind the fine gas cleaning system, a separator of water drops is usually arranged to dewater the gas.

**Equipment for pressure increasing in the blast furnace**

The equipment for pressure increasing in the furnace is located behind the gas cleaning system and acts also as the last step of gas cleaning. Two various systems are used for the given purpose:

- The equipment called the “expansion station” or “expander”; as a matter of fact, this is a choking system. This is a horizontal cylinder (of 1200 mm diameter) arranged in the gas piping behind the gas cleaning equipment, which is closed with a blanking panel with several holes fitted with regulation dampers. Three throttle valves are controlled automatically or from the control centre. One valve with a smaller diameter is adjusted for half a flow of gas and one valve in the bottom part acts as a safety passage for gas and water. Before regulation dampers, water is injected perpendicularly to the flow direction in order to protect sealing areas against wear and, at the same time, this acts as the last gas cleaning step.

- Expansion turbines use pressure and thermal energy of the gas for electrical energy production.

In modern blast furnaces, the blast furnace gas thermal and pressure energy is not changed to an idle heat by choking, but it is used for electrical energy production in the
expansion turbine. Axial and radial expansion turbines are used and their advantage is reduction of energy demandingness of pig iron production.

The general scheme of the blast furnace gas cleaning used in the Czech Republic is shown in Fig. 20.

Fig. 20 Scheme of the blast furnace gas cleaning used in the Czech Republic

Questions:
1. How much dust does the unrefined blast furnace gas contain?
2. Which forces are used for the blast furnace gas preliminary cleaning?
3. What is a principle of operation of the Venturi jet washer?
4. What is the final cleanliness of the blast furnace gas?
5. What is an advantage of expansion turbines?
8. TECHNOLOGICAL FAILURES OF THE BLAST FURNACE

Subchapters:
- Blast furnace cold run
- Blast furnace hot run
- Liming of the blast furnace
- Encrustation of the hearth
- Hearth lining damage
- Accretions in the blast furnace

Lecture

A technological failure of a blast furnace is any restriction or interruption of production caused by reasons different than a failure of machinery equipment of the blast furnace or its accessories. Each such failure results in production loss, increased specific consumption of fuel and impaired quality of pig iron. To avoid economic losses, it is necessary to prevent such failures or to suppress them immediately at the beginning.

**Blast furnace cold run**

The cold run is a name for such a sudden cool-down of the bottom part of the blast furnace, when solidification of the liquid iron and slag in the hearth threatens and the charge descending is hindered or blocked.

Symptoms of the cold run: slag colour gets dark or black, which is caused by an increase in a proportion of iron oxides direct reduction; reduced brightness of coke lumps in oxidation zones and dark pieces of non-molten charge; low temperature of liquid iron, high content of sulfur in liquid iron, low content of silicon and manganese, decreased temperature of gas in the top; in a critical case flooding of tuyeres, sometimes even of injection pipes, by the slag, often mixed with the liquid iron, the liquid iron and slag tapping is made impossible.

Reasons of the cold run – water from defective valves leaking into the furnace inner space, a wrong calculation or weighing of the charge, sudden worsening of the coke quality, a release of an accretion from the furnace wall, too intensive run of the furnace, strong peripheral run of the furnace, excessive amount of injected substitute fuels without the particular increase in the blast temperature or its enrichment with oxygen, adaptation of the furnace to high pressure without modification of dumping and others.

Actions for the restoration of the initial condition: if the cool-down is not too intensive, when tapping can be carried out, a proportion of coke in the charge needs to be increased, possibly to charge several coke charges. Wrong charge composition must be corrected, defective valves must be replaced, blast moisturizing must be stopped, its temperature increased and enriched with oxygen. A decrease in intensity of blast blowing can help, too. In the case that the liquid products do not flow out and flooding of tuyeres occurs, the blast furnace must be stopped, tuyeres cleaned and filled with a refractory mass. A small hole is left in the tuyere above the liquid iron taphole and blowing of very hot blast enriched with oxygen must be restored. If the liquid iron taphole cannot be burnt-through, an emergency taphole must be burnt-through. Tappings of the liquid iron and slag are carried out within short intervals and the regular taphole can be used only after an adequate increase in temperature of the liquid products. Gradually, side tuyeres are put into operation one after another. The standard operation restoration can last several days up to several weeks.
Blast furnace hot run

The hot run is the opposite to the cold run.

Symptoms of the hot run: strong brightness of the coke circulating in the oxidation zones, bright to white alkaline slag, a high content of silicon and manganese in the liquid iron and its high temperature, a low content of sulfur, stopping of descending of the charge, a necessity of jumping of the furnace.

Reasons of the hot run: excessive amount of fuel in the charge, another mistake in the composition or weighing of the charge components, stopping of substitute fuels injection without stopping oxygen etc.

Actions for the restoration of the initial condition: a charge composition correction, an increase in blast moisture, a decrease in blast temperature, a reduction of oxygen concentration in the blast.

Liming of the blast furnace

Liming of the blast furnace is a technological failure caused by the excessive basicity of slag, which flows out with difficulties and immediately changes into dust or does not flow out at all. A reason is usually a wrong composition or weighing of the charge. If the liquid products can be drained out, although with difficulties, liming can be remedied by a highly acidic charge and the increased fuel consumption. In other case the procedure is the same as in the cold run.

Encrustation of the hearth

Encrustation of the hearth is the hearth volume reduction as a result of a formed accretion, resulting in overall tuyere burn. A cause is usually a bad coke quality or the hearth cool-down by leaking-in water. To restore the normal condition it is necessary to increase the manganese content in the charge temporarily (to flush the hearth), to work with more acidic slag, to increase temperature in the hearth and shorten the interval between tappings.

Hearth lining damage

A damage of the carbon lining in the hearth is a defect, which can have serious consequences, even the hearth breakthrough. It can be caused by a temperature inhomogeneity etc. It can be found out from increasing temperature on the respective thermocouples or their destruction. To restore the normal condition it is necessary to transport TiO₂ or ilmenite to the hearth. In the technology with the coal injection into the furnace, it is possible to inject titanium along with coal. Injection is performed through several tuyeres, so that the defect is positioned between these tuyeres and the liquid iron taphole. If the injection through tuyeres cannot be performed, the titanium compound is fed by means of the charge. Ilmenite or titanium agglomerate is added to the charge approximately 8 hours prior to the scheduled stopping of the furnace. Beforehand, the coke amount in the charge must be increased, so that the higher temperature supports the titanium reduction. When the reduced titanium is in the hearth, the furnace gets stopped, the temperature drops and the formed titanium carbonitride is condensed on the hearth walls, thus preventing further damage of the hearth.

Accretions in the blast furnace

Formation of accretions in the blast furnace is one of the most serious causes of production and economic losses in the pig iron production. Most accretions are formed in the bottom part of the shaft and gradually propagate to the central and upper part. Above the root part of the accretion, which firmly adheres to the lining, loose material markedly changing the working profile of the blast furnace is usually piled up. In some cases, a thin but hard crust is formed on the entire inner surface of the accretion, which stabilizes the accretion. Thin accretions hardened across the whole cross-section are called brush matting and they are usually useful, because they protect the furnace lining against damage (bosh, belly).
A shape of accretions can vary, however, the most frequently it is an annulus shape of a thickness from 1 to 6 m. One-sided accretions have still larger sizes.

Accretions in the blast furnace show various symptoms depending on their shapes and dimensions, however, they always cause an irregular run of the blast furnace. Typically a temperature field in the top is changed dramatically, as well as temperature distribution and CO₂ content in the horizontal cross-section of the shaft found out using horizontal probes. The lining temperature always decreases, the throat dust amount increases. Hanging of the charge occurs, which requires “jumping” of the furnace, when partial release of an accretion and cooling-down of the bottom part of the blast furnace may occur. Jumping of the furnace is a short-term reduction of the blast pressure. The gas pressure from the top downwards releases an accretion, which drops to the bottom part of the furnace. Interventions through a change in dumping are usually only a little effective.

Causes of formation of accretions:
- Presence of alkalis in the charge
- Presence of zinc in the charge
- Improper strength characteristics of coke and ore parts of the charge
- Long-lasting inner run of the furnace with hanging of the charge
- Extreme outer run of the furnace, when the slag is taken down by the gas into the lower temperature regions, where it solidifies
- Oblique direction of run in the furnace
- Water leaking-in to the furnace
- Long-lasting shut-down of the furnace without a proper thermal preparation
- Highly basic slag near the furnace wall
- Suddenly cooled primary slag with a high FeO content, solidifying as a result of the increased direct reduction

Methods of intensification of accretions are based on a measurement of temperature of the lining or of the outlet cooling water, on a measurement of temperature and a content of CO₂ in the gas in the horizontal cross-section of the shaft etc. Reliable results can be achieved by drilling in the shaft lining and subsequent inserting a steel bar into the blast furnace inner space. In places with the flowing gas, the bar is brought to a great heat after a short time, while in other locations remains cool.

Methods of removal of accretions during the full operation of the furnace, e.g. by intensification of circumferential gas flow, jumping of the furnace or reduction of the cooling water inlet into a particular location, are not always effective and accretions are removed pyrotechnically after partial blowing-off and shutting-down of the furnace.

**Basic technical-economic indicators of the pig iron production**

Productivity, consumption and cost parameters belong among basic technical-economic indicators of the pig iron production. However, as the price of the produced pig iron depends on its grade, homogeneity of chemical composition and temperature of iron belong among the technical-economic indicators, too.

The **specific consumption of coke** is the coke consumption recomputated per a unit of the produced pig iron.

The **specific consumption of fuel** is the coke and substitute fuels consumption recomputated per a unit of the produced pig iron.

The **specific ratio of slag** is the formed slag amount recomputated per a unit of the produced pig iron.
The daily productivity of the blast furnace can be expressed by a ratio of the coke consumption per day ($K_d$) to its specific consumption ($k_m$).

$$P_d = \frac{K_d}{k_m} \quad (\text{t.d}^{-1})$$

For evaluation of the operation intensity of blast furnaces of different sizes, the volume coefficient of the coke burning intensity is used

$$I = \frac{K_d}{V_0} \quad (\text{t.m}^{-3}.\text{d}^{-1})$$

where $V_0$ is a useful volume of the blast furnace, or the hearth loading surface index

$$i = \frac{K_d}{A_n} \quad (\text{t.m}^{-2}.\text{d}^{-1})$$

where $A_n$ is a hearth cross-section area in the plane of tuyeres.

A coefficient of utilization of the blast furnace useful volume ($k_0$ or KIPO) is given by a ratio of the furnace useful volume to its productivity per day

$$k_0 = \frac{V_0}{P_d} \quad (\text{m}^3.\text{t}.\text{d})$$

The inverse value of this parameter, called the specific productivity parameter, has the same importance.

$$P_m = \frac{P_d}{V_0} \quad (\text{m}^3.\text{t}.\text{d})$$

Questions:

1. Where is the slag separated from the liquid iron?
2. What is the blast furnace cold run and what are its causes?
3. How can the blast furnace cold run remedied?
4. What is the blast furnace hot run and what are its causes?
5. How can the blast furnace hot run remedied?
6. How is the problem of carbon sedimentation and dissolution in the blast furnace hearth solved?
7. What are causes of formation of accretions in the blast furnace?
8. What does it mean – jumping of the blast furnace?
9. What are basic technical-economic parameters of the blast furnace operation?
9. BLAST FURNACE LINING

Subchapters:
- Function of the blast furnace lining
- Influences on the blast furnace lining
- Lining of the blast furnace in its particular zones
- Tamped hearths
- Hearths from carbon and graphite blocks
- Wear of the bottom and hearth

Lecture

A length of the blast furnace campaign is limited by its lining operating life. The lining quality and operating life is decisive also for the blast furnace operation safety.

The blast furnace lining ensures mainly the following functions:
- A decrease in intensity of heat transfer from reduction gases in the blast furnace to the cooling system
- Protection against wear of the cooling system elements by mechanical abrasion of charged raw materials and by effect of hot gases
- Protection against the direct contact of the cooling system with the liquid iron and slag

The following influences affect the blast furnace lining in particular:
- Temperature and its changes
- Gas pressure and charge pressure
- Mechanical effects of the charge and gas flowing (abrasion, impacts, vibrations etc.)
- Chemical effects and oxidation of CO₂, H₂O, Fe₂O₃
- Disengagement of zinc and carbon causing cracking of brickwork
- Effects of alkalis
- Dissolving of brickwork by effect of liquid iron and slag
- Breaking of brickwork as a result of insufficient joints

In various places and horizons of the blast furnace various influences affect the lining, therefore different requirements are laid on the lining in different places. The given influences depend on temperature.

A rate of attacking the blast furnace lining along its height is depicted in Fig. 21.

In the past, chamotte was used for lining of the upper stack, a proportion of Al₂O₃ was increased in the direction downwards to the belly, down to the corundum in the section of the belly and bosh. The blast furnace hearth and pad were fitted with carbon rammed lining.

The conventional materials with low thermal conductivity – chamottes and high-clayey materials – do not meet the needs anymore due to their short operating life (do not maintain a stable profile).

For this reason they have been replaced by materials with high thermal conductivity based on carbon, graphite and SiC.
SiC has thermal conductivity ten-fold higher than chamotte and five-fold higher than corundum (Al₂O₃), the same as some carbonaceous materials, but substantially lower than graphite.

Many refractory materials were developed, mainly based on SiC with a bond by silicon nitride Si₃N₄. These materials in a combination with intensive cooling (new types of coolers) lasted for 15 up to 20 years.

SiC-based “Sialon”-bonded materials have high thermal conductivity (25 – 30 Wm⁻¹K⁻¹), they are applied with intensive cooling and high thermal drops, but have better properties than nitride-bonded materials.

Sialon: \[ \text{Si}_6z \text{Al}_2 \text{O}_{z} \text{N}_{8-z} \] where \( z = 0 \) to \( 4.2 \)

if \( z = 0 \) => Si₃N₄ - nitride bond

In contrast to conventional materials, where high thermal conductivity is demanded (temperature solution), the use of materials with low thermal conductivity (isolation solution) is considered to the future, which markedly reduce thermal losses and maintain high resistance even at high temperatures. Examples are corundum-based Sialon-bonded materials with thermal conductivity about 3.5 Wm⁻¹K⁻¹. They maintain high resistance against alkalis, liquid iron, slag, etc. even at high temperature. They are applicable as a substitute for carbon linings.

Very harsh conditions for lining are in the bosh, belly and bottom part of shaft zones, therefore various types of lining have been used. Nowadays these parts of the blast furnace are equipped with very effective cooling through copper coolers. The coolers are sprayed with a temporary refractory matter. As a result of intensive cooling, an accretion (brush matting) is formed on copper cooling plates, featuring better properties than the used lining.

**Lining of the hearth walls and pad**

The blast furnace campaign length is determined by the hearth operating life, which is mainly limited by the method and quality of the lining and the blast furnace cooling.

The blast furnace hearth lining has to:
- Prevent the hearth wall break-through
• Ensure continuous operation of the hearth
• Reduce heat losses, so that they do not influence metallurgical processes in the hearth

In the Czech Republic, a hearth with carbon rammed lining was used for a long time. The rammed lining comprised ground coke, graphite and tar. Under continuous heating using gas burners, the mixed mixture was rammed down in place manually at first, later by mechanical tampers, gradually, one layer after another, until the entire walls and pad lining volume was filled as one monolithic block.

Although there were relatively good experience with rammed hearths in the Czech Republic, the technological development has overcome this method and nowadays actually all blast furnaces are equipped with hearths with carbon and graphite blocks.

The main disadvantages of the rammed hearths:
• Relatively low thermal conductivity of the rammed lining (high height of the blast furnace)
• High consumption of manpower in unhealthy atmosphere
• Uneven quality of the rammed lining (non-controlled graphitization during the blast furnace operation)

An example of the rammed hearth is in Fig. 22.

An advantage of graphite and carbon blocks is that their thermal conductivity is known beforehand, which enables to place the particular blocks in accordance with a needed cooling intensity, higher thermal conductivity, which enables to reduce the lining thickness, and also an easier installation of the hearth lining. A disadvantage of existence of joints between the particular blocks is minimized by high accuracy in their production. In order to improve the function and operating life of graphite and carbon blocks, their surface is processed to reduce porosity at present. Very finely ground material is rubbed in the surface of carbon or graphite blocks in order to fill the open pores, leading to reduction of the contact surface area between the hot metal and lining and a decrease in erosion. In the USA, blocks of significantly smaller dimensions are used, on which porosity is reduced by pressing the particular blocks under high temperatures, thus closing the pores on the surface. Such processed products are called microporous.

![Fig. 22 Rammed hearth used in the Czech Republic](image_url)
An example of nowadays method of the blast furnace hearth walls and pad lining is depicted in Fig. 23.

![Diagram of blast furnace hearth walls and pad]

**Fig. 23** Design of the hearth walls and pad in the blast furnace no. 2 in Bremen iron and steel works

In spite of all the effort to ensure the lining surface quality, wear and damage of the hearth walls and pad lining occurs.

The most frequent causes of wear are as follows:
- Penetration of liquid iron to the lining
- Dissolution of carbon of the hearth
- Effect of alkalis
- Lining carbon oxidation

Two typical ways of the hearth wear are depicted in Fig. 24. The wear profile “a” is typical for larger blast furnaces and is called the “elephant foot”. This wear is mainly in corners of the hearth; the column of coke (dead man) prior to opening a taphole is floating and after the tapping is sitting on the pad, a free space occurs in the corners, through which the liquid iron flows intensively. This leads to erosion of carbon from the lining and subsequent wear. The other wear profile “b” is typical for smaller (also Czech) furnaces, where the dead man does not float, but sits on the blast furnace bottom all the time.
Transition of the Czech blast furnaces from the tamped hearths to the blocks enabled to reduce the blast furnace bottom height and increase the dead space depth (ash-pan). This, along with better cooling of the hearth pad, has contributed to stabilization of thermal and hydrodynamic conditions in the hearth and has established presuppositions for a longer campaign of the blast furnace.

**Questions:**

1. What is purpose of the blast furnace lining?
2. Which are demanded properties of the shaft lining?
3. Which are demanded properties of the hearth lining?
4. What does the expression “Sialon” mean?
5. What is used for lining of the blast furnace hearth walls and pad?
6. What are advantages and disadvantages of tamped hearths?
7. What are advantages and disadvantages of block hearths?
8. What phenomenon is called an “elephant foot”?
10. COOLING OF THE BLAST FURNACE

Subchapters:
- Classification of cooling systems
- Horizontal cooling system
- Vertical cooling system
- Combined cooling system
- Cooling of the blast furnace bottom
- Evaporative cooling

Lecture

The blast furnace lining operating life depends on the cooling method and quality. The entire blast furnace has to be cooled, from the bottom up to the upper part of the shaft. Aside from the lining, bell-less top, tuyeres and hot blast slide-valves are cooled, too. The slag taphole was also cooled in the past.

Cooling systems can be divided:

According to the cooling medium
- Flow-through, open
- Flow-through, closed
- Evaporative cooling
- Cooling of the bottom – water, air, oil

According to the used cooling elements
- Shell cooling, open
- Shell cooling in closed cooling boxes (with a double skin)
- Cooling wedges
- Cooling plates
- The bottom – cooling plates, pipes, staves

The blast furnace cooling can be one-pass (from one source) or two-pass.

According to the cooling type and the used cooling elements, we can divide:

**Horizontal cooling system** (cooling wedges)

Advantages of the horizontal cooling system are in a large cooling surface (up to 3 m²·m⁻³ of lining), a possibility of easy replacement of cooling elements and a possibility to maintain the designed working profile of the furnace more permanently. A disadvantage is an insufficient tightness of the furnace shell caused by large cutouts in the shell, a decrease in the shell bearing capacity and an increased danger of burnt valves after the lining wear or release of accretions.

An example of a design of a replaceable cooling wedge is shown in Fig. 25.
**Vertical cooling system** (cooling plates)

In the vertical cooling system the plate coolers are placed on the inner side of the furnace shell. There are only openings for water inlet and outlet in the shell, so there is no decrease either in strength or in tightness in the shell. The cooling surface is smaller (about 2 m²/m³ of lining). This system is suitable for blast furnaces working with high pressure on the top.

The conventional cooling plates were manufactured from cast iron; at present, mainly for thermally exposed zones, they are made from pure copper. As they keep in the lining worse, they are sometimes fitted with a “ledge”, in some cases with grooves for the lining. Modern coolers have a separate cooling water circuit for cooling of the ledge, possibly for various parts of the cooling plate. Cooling plates are not replaceable, in a case of a failure the water inlet and outlet must be blinded and the shell in that place must be cooled on the surface. A critical point is also a passage of the inlet and outlet pipe through the furnace shell. Mechanical damage of pipes may occur as a result of thermal dilatation. Examples of cooling plates are shown in Figs. 26 and 27.
Combined cooling system

Nowadays a combined horizontal-vertical system is used very often, taking advantages of both the systems.
The use of a combined system for a blast furnace shaft cooling is shown in Fig. 28.
Cooling of the blast furnace bottom

In the past the bottom of the blast furnace was usually cooled by air, in order to prevent burning of the bottom and hydrogen explosion when using cooling water. Also, a two-pass cooling was used – the upper part by air or oil, the bottom part by water. Today water cooling is used, using pipes, staves or coolers.

Examples of the blast furnace bottom cooling are shown in Figs. 29 and 30.
Fig. 29  Blast furnace bottom cooling according to Gipromez design

Fig. 30  Modern method of the blast furnace bottom cooling
Evaporative cooling

A principle of evaporative cooling is heating of the cooling water in cooling elements up to its boiling point. It allows at least partial utilization of the water latent heat (2440 kJ/kg). In the evaporative cooling the water consumption decreases many times. In flow-through cooling the water in coolers is heated only by about 5 °C in order to avoid sediment incrustation. This means that 1 kg of water carries away only about 21 kJ. In a case of the evaporative cooling, at input temperature of 20 °C 1 kg of water carries the following amount of heat:

\[ Q = 4.1868(100 - 20) + 2440 = 2775 \text{ kJ}. \]

This is 132-fold higher than in the flow-through cooling. Actually, only a part of water is evaporated in the cooling element and water circulates in the circuit several times, so the amount of carried heat is lower. However, the water consumption in the evaporative cooling is only a fragment of the consumption in the flow-through cooling. If water in the system was heated to more than 100 °C, the overheated steam energy could be used in the condensation turbine for electric current production. However, the system would have to work in the overpressure regime, with a danger of a high amount of steam penetrating into the blast furnace in a case of rupture of a pipe in the cooler and an ensuing risk of explosion.

A necessary condition for the evaporative cooling is chemical treatment of water and deoxidation. The evaporative cooling system differs from the flow-through system also by a possibility of the automatic control of cooling to the same intensity, because along with an increase in thermal stress, the evaporated water amount is increased automatically, too.

The evaporative cooling is only used for cooling of some parts of the blast furnace and for cooling of hot blast valves. In some cases the evaporative cooling can cool too much, which may disturb metallurgical processes in the furnace.

Questions:

1. What are advantages of the horizontal cooling?
2. What are advantages of the vertical cooling?
3. What material are coolers made from?
4. How are the blast furnace bosh and belly cooled?
5. What are advantages of the evaporative cooling?
Recommended and used literature:


