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DRY SLAG GRANULATION AND ENERGY RECOVERY

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Introduction

Paul Wurth has approached the topic of dry slag granulation with a simple but effective method in which where steel spheres and liquid slag are mixed to achieve fast cooling of the blast furnace slag while creating a product with highest possible energy content.

Following different test series, where the slag quality and suitability for cement production was proven, Paul Wurth built a full scale dry slag granulation pilot plant at ROGESA's BF4. The first phase of this pilot plant was successfully put into operation end of 2013 and is able to process up to 8 t/min of liquid blast furnace slag.

Traditional Slag Handling

Blast furnace slag is either cooled down in slag pits or it is quenched in water. Cooling in slag pits with no or little water spraying causes the slag to solidify relatively slowly, providing sufficient time for the molecules to organize themselves in a crystalline structure. Crystalline blast furnace slag is a rather coarse material which can be used for rail, road and other construction work.

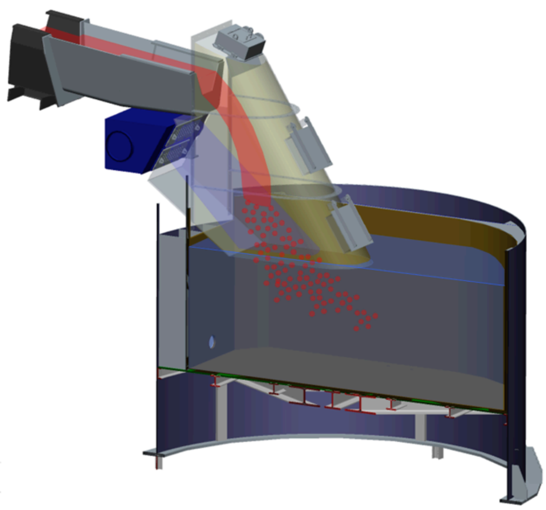

Figure 1: Paul Wurth INBA© slag granulation

If slag is quenched with water, it is cooled down too fast for the molecules to organize themselves in a crystalline structure. Hence they are solidified in amorphous or vitreous form, in which the product is called Granulated Blast Furnace slag (GBFS). GFBS is a valuable raw material for the cement industry. It replaces clinker in the cement to a large percentage and gives the cement attractive properties. Figure 1 shows the functional principle of a Paul Wurth INBA© slag granulation system.

Replacement of the clinker means: the raw material does not need to be mined and does not need to undergo calcination, so that the use of GBFS in the cement industry is a huge contribution to save energy and to reduce CO_2 emissions. This all being valid for water granulated slag, the benefits can be topped by adopting a dry slag granulation technology with energy recovery in order to recover the sensible heat from the slag, which is leaving the blast furnace at approximately 1500 °C.

Dry Slag Granulation

Advantages

Such a dry slag granulation process accumulates many advantages in comparison to the process of water granulation:

- No water consumption
  In the traditional wet granulation process, approximately 0.7 m^3 of water is evaporated to solidify 1 ton of blast furnace slag. The Paul Wurth dry slag granulation process uses only a very limited amount of water for cooling mechanical parts.
- Heat recovery possible
  The heat content of one ton of blast furnace slag amounts to 1.800 MJ. For an average size blast furnace, the daily average thermal power output reaches 30 – 40 MW. In a dry granulation process this energy may be recovered and used in other processes.
- Reduced sulphurous emissions
  During wet granulation of blast furnace slag, H_2S and SO_2 emissions occur due to the contact of between water and slag. The use of a condensation tower for reduction of sulphurous emissions is mandatory in many legislations. In the dry slag granulation process, the slag is not in direct contact with water and thus the main reason for the creation of these emissions is resolved.
- No drying costs in cement plants
  In contrary to traditional GBFS which is delivered to cement plants at about 10 % humidity, dry granulated slag does not need to be dried in the cement plants and thus reduces CO_2 emissions even further. Furthermore, transport costs are lower because no water needs to be transported to the cement plants.

- Better product handling

  The dry product features several advantages when it comes to product handling. First of all, the lack of product humidity together with a slightly coarser grain size distribution and the amorphous structure avoid any freezing or bulk solidification during longer storage periods. Furthermore, the product features a slightly higher bulk density than GBFS (1.4-1.5 t/m^3 as opposed to 1.0-1.1 t/m^3 for GBFS).

Preconditions

A dry slag granulation technology needs however to fulfil three main preconditions which are fundamental for the success of such technology:

1. Guarantee the vitreous solidification form by quenching the slag, because the product value of the GBFS surpasses the value of the recovered energy.
2. Cope with the cyclic operation of the blast furnace.
3. Provide the recovered energy at high temperature and at high and constant flux rate.

Fulfilling these preconditions is especially challenging because of the unfavourable physical proper-ties of liquid blast furnace slag:

- Low thermal conductivity. As nonetheless fast cooling speeds need to be achieved in order to guarantee vitreous solidification, the maximum slag layer thickness in any dry solidification process is very limited
- High thermal capacity. The thermal capacity of slag is significantly higher than the thermal capacity of metals.
- High viscosity. Liquid blast furnace features a very high viscosity which is also very much dependent on temperature and slag chemical composition

So any dry slag granulation technology needs to cope with these unfavourable conditions. The liquid blast furnace slag, which is leaving the furnace at variable flow rates and physical properties, needs to be safely cooled in a way that guarantees vitreous solidification as well as highest possible exergy content.

The Paul Wurth Mixing Method for Dry Slag Granulation

Paul Wurth has approached the subject of dry slag granulation a radically new concept: the mixing method.

The basic principle of the mixing method is straight forward: liquid slag is mixed together with steel spheres in a way to generate a homogenous mixture between slag and said steel spheres which act as cooling elements by providing a sufficiently

large contact surface for efficient heat transfer. This ensures rapid cooling of the blast furnace and provides the mixture at high temperature.

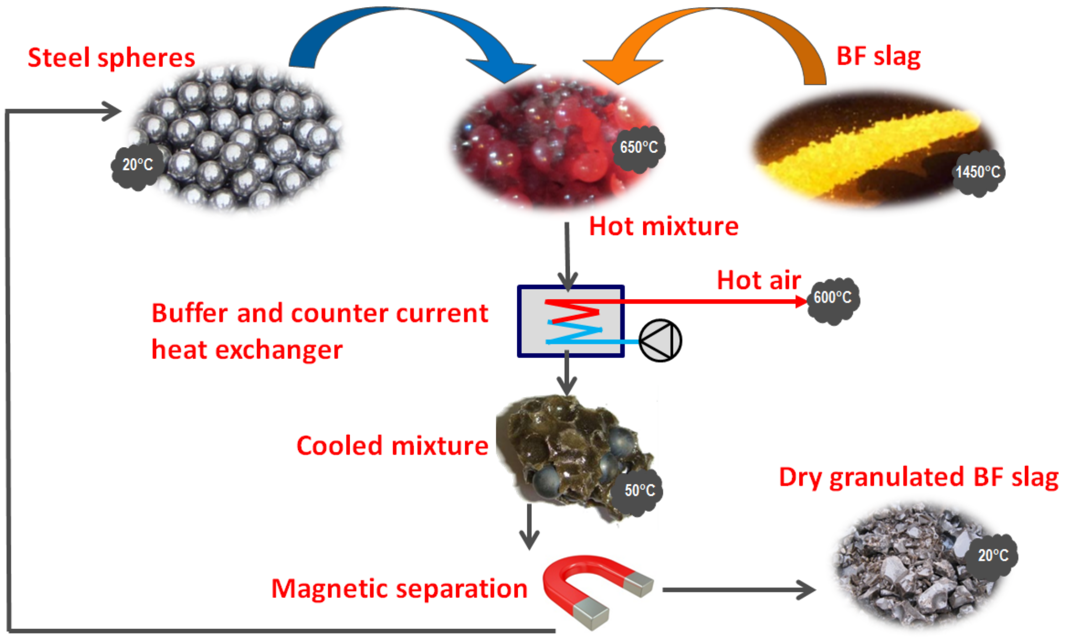

Figure 2: functional principle of the Paul Wurth dry slag granulation method

Figure 2 shows the functional principle schematically. Liquid blast furnace slag at high temperature is mixed evenly with cold spheres. This is implemented by pouring the liquid slag into moulds of a slag caster, measuring the height of the liquid slag in said moulds and adding the steel spheres evenly over the whole cross surface of a mould. Due to the high contact surface provided by the steel spheres, the heat transfer from the slag to the steel spheres is fast enough to guarantee vitreous solidification of the slag. Furthermore, the resulting mixture of steel spheres and solidified slag is at elevated temperature and thus suitable for efficient heat recovery.

The temperature of this mixture depends on the physical properties as well as on the chemical composition of the slag. For blast furnace slag it is usually around 650°C. Said mixture breaks easily apart upon impact on a rigid surface and is then fed to a counter current heat exchanger that then provides a cooled mixture and hot air for further processing. The steel spheres are easily separated from the mixture by magnetic separation and fed back to the process.

Fulfilment of Preconditions

The previously mentioned necessary preconditions are fulfilled by the mixing method:

1. Vitreous solidification of the blast furnace slag
   High cooling speed is the key to vitreous solidification of the slag. To compensate for the low thermal conductivity and the high thermal capacity of the slag, at given temperature levels, physics only offers a large heat transfer area as compensation. This is achieved with the homogenous distribution of steel spheres in the liquid slag. The same principle applies to water quenching where the high pressure water jets disintegrate the slag stream for creating a large heat transfer contact surface. The steel balls, dropped into a mould filled with liquid slag, offer a solid and robust solution for providing the required heat transfer area. The density difference between liquid slag and steel balls is sufficiently high so that even high and varying slag viscosity does not pose any problem. The steel balls penetrate evenly and homogeneously at all temperature levels above 1330 °C.
2. Coping with the cyclic operation of the blast furnace
   The answer is to take the slag as it leaves the furnace, regardless of flow and temperature. Buffering is shifted behind solidification, when there is a coarse, solid product, which can be stored and handled without problems. Again the mixing method is robust enough to deal with varying slag flows and temperature conditions.
   Any process technology which is dependent on flow rate limitations and/or temperature limitations will enforce buffering of the liquid slag. Buffering of liquid slag will cost energy or loss of vitrified product, both strongly influencing the economy.
3. Provide the recovered energy at high temperature and at high and constant flux rate.
   The mixing temperature between blast furnace slag and cold steel spheres lies at approximately 650 °C, which allows energy recovery in form of hot air at a temperature of 600 °C, sufficient for operating a steam turbine or direct use as preheated combustion air. The ingot consisting of steel balls and slag is dropped onto an impact plate where the ingot disintegrates into slag particles and steel balls with a large surface area to allow heat flux rates of 30 to 40 MW transferred from slag and steel balls into the hot air as energy carrier.

Product Quality

Several small scale test series were conducted. During one test series with blast furnace slag, the product quality could be extensively tested in cooperation with

FEhS – Institut für Baustoff – Forschung from Duisburg/Germany. The results are as follows:

- The glass content meets the requirements for the cement industry as in general a glass content of 95 % and more was measured.
- The grindability is comparable to wet granulated slag
- Most importantly, the compression strength and reactivity of the cements produced with dry granulated slag do not differ from cements produced with water granulated slag. Figure 3 indicates the measured values for dry and wet granulated slag samples taken from the same heat.

	BF slag: CEM I = 50:50 Compression strength in MPa			BF slag:clinker = 75:25 Compression strength in MPa		
	2d	7d	28d	2d	7d	28d
Wet granulated 09/02/2012	14.6	35.2	58.8	12.8	28.2	37.7
Dry granulated 09/02/2012	14.3	33.8	57.0	10.4	27.0	38.6

Figure 3: compression strength tests performed on wet and dry granulated slag samples

The Pilot Plant

Engineering and Construction of the First Phase

Following the favourable outcome of the different test series, Paul Wurth found an agreement with ROGESA for implementation of a full scale dry slag solidification pilot plant to be built on their blast furnace BF4 at Dillinger Hütte steelworks in Saarland region, Germany.

The pilot plant will be built in two phases:
The first phase comprises the slag caster able to granulate liquid blast furnace slag at up to 8 t/min in order to produce the hot mixture of blast furnace slag and steel spheres at a temperature of around 650 °C. The slag caster is connected to the cast house of number 4 blast furnace by means of a 30 m long hot runner. In this first phase the continuous energy recovery is not yet installed, the produced hot mixture is however cooled and separated in a reduced scale offline facility. Slag can be received at up to 8 t/min. However, the maximum capacity was limited to 80 t of slag

per day in this first phase. This decision was made in order to limit the amount of steel spheres and the size of the material treatment area for phase 1.

The second phase will upgrade the existing slag caster with the fully automatic energy recovery part able to produce hot air (to be further processed to superheated steam) continuously, even in-between taps. By closing the loop with the fully continuous cooling and mixture separation, the installation will be able to granulate 100 % of the slag from the blast furnace.

Figure 4: front view of the phase 1 pilot plant

Figure 4 shows the front view of the first phase pilot plant. The moulds of the slag caster are clearly visible, as well as the steel sphere bin which holds the steel spheres before they are injected into the liquid slag in the moulds.

Figure 5: cast iron moulds

Figure 5 shows the moulds of the slag caster. A total of 34 moulds are installed and each mould can hold more than 600 kg of liquid slag. Up to 2.000 kg of steel spheres may then be added to each mould. The height of the liquid slag in the moulds is measured continuously with a laser in order to give immediate feedback on the current slag flow rate and the precise weight of steel spheres to be added into that particular mould.

Figure 6 Plate shows the impact plate located on the de-moulding side of the slag caster. The hot mixture easily breaks apart into impact on the rigid surface and may then be carried away for further processing. This is done via front loader in the first phase and with a heat resistant conveyor in the second phase.

The material handling area in phase 1 is an offline solution with reduced capacity. The hot material from the cast is transferred into the cooling bins where it is cooled overnight. The next morning the material is sieved, crushed if necessary, and steel balls and slag are separated by magnet. Figure 7 shows the material treatment area with the cooling bins, the crusher and the magnetic separator.

Figure 6: mixture de-moulding area and impact plate

All major erection works on the pilot plant had been successfully finished by beginning of October 2013. The necessary civil works as well as the steel works were achieved in a total of 8 months.

Figure 7: phase 1 material treatment area for off-line cooling and separation

Commissioning and Results from First Phase

In November 2013 the plant was successfully commissioned. During the first cast 24 tons at a slag rate of 2,5 t/min were cast and safely solidified. Some mechanical issues arose during the first operation hours but could be quickly resolved.

As of July 2014, the plant is running smoothly in fully automatic mode during 2 to 3 casts per week. The maximum slag flow rate of 8 t/min has been reached and solidified safely. Up to 80 t of slag have been granulated during several casts.

Figure 8: slag flow to the installation

Figure 8 shows the slag flow to the installation. The level of the liquid slag is then taken via laser measurement and the adequate number of steel spheres added shortly afterwards via hydraulically activated gates.

The result can be seen in Figure 9 which shows the mixture of steel spheres and solidified slag around 50 seconds after the steel spheres have been injected. A few seconds later the mixture is to be dropped on the impact plate and transported away for further processing.

Figure 9: solidified mixture of steel spheres and slag before de-moulding

Figure 10 shows the mixture at the exact moment when it leaves the moulds. The homogenous distribution of the steel spheres inside the solidified slag can be clearly seen.

Figure 10: solidified mixture of steel spheres and slag at de-moulding

Operational Results

- The handling of the steel balls caused in the beginning some mechanical problems, which could be solved through minor modifications at the caster and other handling equipment.
- Safe and reliable solidification of high slag mass flows of up to 8 t/min has been achieved.
- The steel sphere dosing system fulfils all expectations as it is capable of reliably dosing the right number of steel spheres evenly over the moulds even at highest caster speeds.
- The slag flow detection system via laser measurement works perfectly and the switch to automatic mode could be quickly achieved.
- At present around 3 casts per week are received by the dry slag granulation plant.
- The slag quality (vitrification rate) is still under improvement. Although values of up to 92 % glass content have been measured, these positive results have not yet been delivered at constant rate.

The Second Phase of the Pilot Plant

Phase two of the pilot plant will be tackled once all necessary operational results from the first phase are available. In phase two the heat recovery part will be added in order to make the whole system capable of continuous operation. Figure 11 shows the provisional flow sheet of the second phase of the pilot plant.

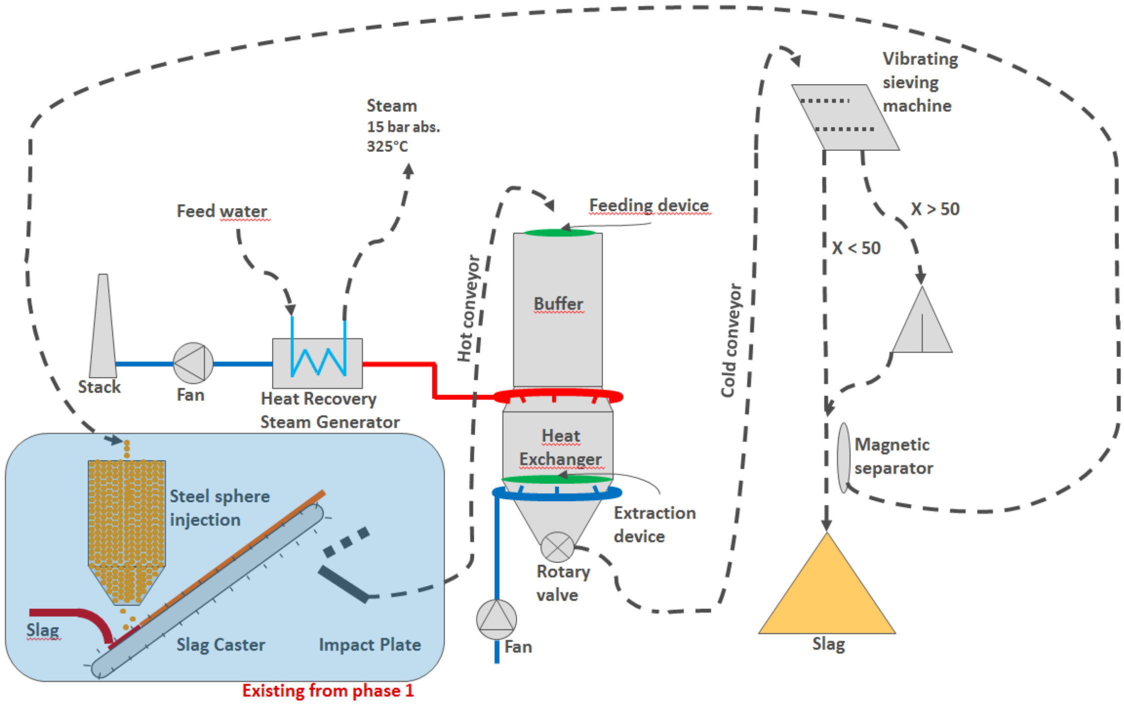

Figure 11: pilot plant - phase 2 flow sheet

From the existing slag caster the hot ingot will drop on the impact plate, will disintegrate and will be transferred by a hot conveyor into the buffer. The buffer is designed to compensate for the normal cyclic operation of the blast furnace. Additionally the buffer will serve as energy storage that allows the steam generator to run at reduced capacity during one or more missed out blast furnace taps.

Below the buffer the counter current heat exchanger is installed in which the energy from the mixture is transferred to hot air at a temperature of approximately 600 °C. The mixture is withdrawn from the heat exchange at a temperature of approximately 50 °C at constant mass flow to provide at the same time a constant energy flow to the consumer.

The flow sheet shows a steam generator as one option for the consumer. In this version superheated steam at 15 bar (g) and 320 °C is produced to be used in the existing steam turbines operating at ROGESA. However, the hot air from the dry slag granulation plant may also be used to preheat the combustion air and the blast furnace gas used in the hot stoves.

The cold material is extracted from the heat exchanger. Most of the steel spheres will have been liberated already from the slag so that those particles can be sieved off.

The balance of material will run through an impact crusher where final liberation will occur. Thereafter a magnet will separate steel spheres from the slag. Finally the steel spheres will then be recirculated to the process, thus closing the circuit and allowing continuous operation of the plant.

Conclusions

- The mixing method as process for dry slag granulation with energy recovery produces cement quality vitrified slag.
- It is not affected by varying slag flows, varying temperatures and varying chemistries of the slag.
- It provides steady energy output from the heat recovery due to a buffer, which is compensating the cyclic BF production by storing the hot but solid mixture of slag and steel spheres.
- The process has been successfully tested for BF slag, BOF slag, EAF slag and FeNi slag.
- The mixing method is the most robust process in the market.