General
We encounter bulk solids every day in mineral and non-mineral form – from, for example, mining (ores, coal) through building materials (cement) to foodstuffs (sugar, coffee, cereals) and chemical or pharmaceutical products (pigments, pills).

The properties of bulk solids are determined and characterized based on particle size, particle distribution, bulk density, angle of repose, moisture content and temperature. Amongst other things, these parameters determine the flow behaviour and flowability of bulk solids, and therefore have a crucial influence on the process engineering and equipment used in the processing of these coarse-, fine- and ultra-fine-grained materials. The design of thermal processing plants for the heat treatment of bulk solids must also be adapted to the characteristic properties of the materials. Typical kiln or furnace applications can be found in the ceramics, glass and binders industry as well as in the chemicals industry, comprising powders, granular as well as lumpy, dry and wet materials.

To ensure the effective mechanical and thermal treatment of the multitude of different bulk solids, a correspondingly wide range of different industrial kiln and furnaces [1] with different conveying systems are available as rugged production plants. In the following, the main types of kiln and furnace for drying, debinding, calcining, and sintering of bulk solids to application temperatures up to 1800 °C and in different atmospheres are examined in greater detail. A basic differentiation is made between intermittently and continuously operating kilns and furnaces.

Rotary and pendulum kilns
The key characteristic of rotary and pendulum kilns is that the bulk solids are kept in constant motion during heat treatment. The kilns are operated continuously, allowing direct transport of the bulk solids through the kiln. In the rotary kiln, the inclination of the rotary tube over its length and the rotational speed are adjusted to the bulk solid to be treated. Depending on the type of heating, a differentiation is made between directly and indirectly heated rotary kilns. Indirectly heated rotary kilns are used particularly when the feed material is prone to severe dust generation, must undergo a defined temperature profile or has to be treated in special processing conditions, e.g. inert or protective atmosphere. The rotary tube is heated from the outside by means of burners or electric heaters. Depending on process requirements, heating is divided into several control groups over the length of the rotary tube. Depending on the process requirements with regard to max. temperatures,
atmosphere and bulk solids properties, metallic rotary tubes are used up to 1150 °C. Ceramic tubes are used to protect the product against contamination and allow much higher temperatures than metal tubes. However, ceramic tubes are limited with regard to the geometry with which they can be fabricated. Especially for the use of protective gas as the reactive gas, tubes made of graphite are used. In this case, the sealing of the rotary tube is especially important to protect the kiln against leakage and minimize the necessary process gas volume flow. Characteristics of indirectly heated rotary kilns are:

- Application temperature: 650–1600 °C
- Heating: fuel, direct
- Tube material: steel, ceramic, graphite
- Protective gas operation: oxidizing, inert, reducing
- Tube seal: mechanical seal, sealing gas
- Mechanical effect on the product: high
- Degree of automation: high, fully automatic material feed and discharge is possible.

Another model of kiln is the internally heated rotary kiln, which basically has a rotary or pendulum tube with an insulating refractory lining. The insulation is used primarily for heat protection, but, however, also has to be designed as wear protection or an inert protective barrier between the tube and bulk solid. Tubes of this type are heated directly at the front end with a burner. Generally, the burner gases or flue gases are fed in a counterflow to the direction of product transport.

Among the internally heated rotary kilns, there is another special kiln design with a characteristic pendulum movement of the tube, which is therefore termed a pendulum kiln. The pendulum movement of the tube enables the burners or electric heating elements to be arranged lengthwise over the top of the pendulum kiln. This allows the setting of a selective temperature curve over the length of the kiln, which is not possible in the case of internally heated rotary kilns.

Fig. 1 shows a DRI rotary kiln with burner heating and temperature tracking by means of pyrometers. The tube is mounted onto a support frame for optimal adjustment of the angle of inclination to the bulk solids to be transported. The tube is sealed at each end with so-called sliders, which also have suitable equipment for material feed and discharge. As the firing chamber and heat treatment chamber form one unit in the rotary tube of this type of kiln, the process temperature profile is essentially defined by the selected burner configuration and the form of the burner flame.

Characteristics of directly heated rotary kilns are:

- Application temperature: 650–1600 °C
- Heating: electric or fuel, indirect
- Tube seal: mechanical seal, sealing gas
- Mechanical effect on the product: high
- Throughput rate: medium to high, depending on the product
- Degree of automation: high, optionally available with fully automatic material feed and discharge.

For bulk solids that are, for example, prone to severe abrasion as a result of the rotating flow in the tube or start sticking during heat treatment, rotary kilns are generally not used, here tunnel kilns are favoured.

**Tunnel kilns**

Tunnel kilns for thermal processing of bulk solids are used industrially in different models up to firing temperatures of 1800 °C. Typically, the kiln is named after the principle of continuous conveying, for example by means of pusher plates, powered roller conveyer or kiln cars.

Tunnel kilns for the transport of bulk solids through kilns are used whenever large throughput rates must be realized energy efficiently and the feed material consists of shaped products that may not be exposed to any additional mechanical load. Traditionally, bulk catalysts and ceramic grinding beads are sintered in this way. Fig. 2 shows a typical car structure with deck. This is configured as a “setter tray” into which the green products are filled and then sent through the kiln. The burners arranged at the side of the kiln fire below the deck and above the bulk solids. As a result, the bulk solids can be heat treated very selectively and evenly. Especially in the case of temperature-critical bulk solids, “dead burning” of the outer areas is avoided because temperature gradients depending on the bed height can be minimized.

Tunnel kilns with car conveying are designed today primarily as automatic heat treatment plants with filling and emptying equipment integrated in the car circuit.

Characteristics of tunnel kilns with car transport are:

- Application temperature: up to 1800 °C
- Heating: fuel, direct
- Kiln atmosphere: adjusted by means of the burner, oxidizing, inert, reducing
- Mechanical effect on the product: low
- Throughput rate: high
- Degree of automation: high, optionally available with fully automatic car loading and unloading.

Tunnel kilns with pusher plate transport are the first choice for the heat treatment of bulk solids especially
when long kiln cycles with low throughput rates or reactive kiln atmospheres have to be realized for heat treatment. Fig. 3 shows a tunnel kiln with pusher plate conveying for debinding, calcining and sintering ceramic powders in ceramic setters up to 1650 °C. The kiln is operated with H2/N2 protective gas [2]. With the sluice system at the entrance and exit, the consumption of the protective gas is minimized. The kiln atmosphere is introduced into the kiln in the transitional zone between high-temperature sintering zone and cooling zone and therefore supports both cooling and gas separation of the two zones. The bulk solid is transported in covered setters, which are stacked on the actual pusher plates. Appropriate filling, cleaning and emptying equipment for the setters is frequently integrated in the pusher plate circuit. Depending on the heat treatment process, pusher plate kilns are primarily equipped with electric heating in combination with inert kiln atmospheres, in which case no gas tightness or lock system is generally required. Characteristics of tunnel kilns with pusher plate conveying are:

- Application temperature: up to 1650 °C
- Heating: electric, fuel direct
- Kiln atmosphere: protective gas or inert
- Mechanical effect on the product: low
- Throughput rate: low – medium
- Degree of automation: high, optionally available with fully automatic filling, emptying and cleaning equipment.

If the heat treatment process, product and atmosphere control allow the relatively heavy pusher plates to be eliminated, tunnel kilns with powered roller conveyors, so-called roller kilns, can be used. This type of kiln is used especially for short firing or sintering cycles and high throughput rates, and they boast very high energy efficiency [3]. The bulk solid is filled into ceramic bowls or crucibles, which are then transported through the kiln in one or more layers by the roller conveyor. Depending on the bulk weight of the product and the crucible size, useful widths of more than 2 m are generally realized today. With the single-layer operation, very high temperature accuracy is realized over the useful cross-section, which leads to very homogeneous product quality especially in oxidation or reduction processes. In the gas-tight version, roller kilns are used mainly for sintering metal powders in N2/H2 protective atmospheres. Fig. 4 shows a roller kiln with automatic transport system for the ceramic crucibles and setters. With the further development of the ceramic roller materials, today heat treatment processes up to 1650 °C can be realized in roller kilns. In addition flexible conveying systems can be installed with appropriate drive partition and control of the conveying speed, which allows complete process separation of the individual process steps.

Characteristics of roller kilns are:

- Application temperature: up to 1650 °C
- Heating: electric, fuel direct/indirect
- Kiln atmosphere: protective gas, or oxidizing, inert, reducing
- Mechanical effect on the product: low
- Throughput rate: medium-high
- Degree of automation: high, optionally with fully automatic filling, emptying and cleaning equipment.

**Intermittent kilns**

The big advantage of intermittent kilns is their flexibility. As a batch kiln, the intermittent kiln is used typically where it is necessary to change firing and atmosphere curves as well as firing cycles as a result of different products. The material to be fired and the insulated kiln chamber undergo the entire heat treatment process together. These kilns are not usually protective gas kilns. They are heated directly with fuel by means of burners. The most important kiln types are top hat kilns, elevator kilns, chamber kilns and shuttle kilns. The name generally depends on the way the bulk solids are fed into the kiln. With the integration of energy recuperation technology, especially for increasing energy efficiency, it has been possible to substantially reduce the traditional disadvantage of intermittent kilns compared to continuous kilns. The development of the burner control and regulation systems as well as the design programs for simulation of flue gas flows in the useful chamber of the kiln have contributed to this.

**For heat treatment in shuttle kilns**, the following technologies are available today:

- Burners with pulse firing
- Modulating burner control
- Individual burner control
- Recuperator burner technology (Reko).

Moreover these kilns are generally equipped with efficient heat exchangers for preheating of the combustion air and with thermal and catalytic post-combustion systems.

Fig. 5 shows a shuttle kiln for multi-layer debinding and sintering of bulk solids and powders in crucibles or setters with recuperator burner technology and consequently at a 40-% lower energy consumption compared to conventionally equipped shuttle kilns. Characteristics of intermittent kilns (shuttle kilns) are:

- Application temperature: up to 1800 °C
- Heating: fuel direct
- Kiln atmosphere: adjusted with the burners, oxidizing, inert, reducing.
• Mechanical effect on the product: low
• Throughput rate: medium, cycle-dependent
• Degree of automation: high, optionally with fully automatic car loading equipment.

Summary
For the heat treatment of bulk solids, the thermal processing equipment must be adapted to properties such as flow behaviour, flowability and the mechanical properties of the bulk solids. In addition, temperature curve and firing time as well as atmosphere control determine the process cycle. Accordingly, complex and highly technical specifications result.

To meet these specifications, a large number of suitable different thermal processing equipment is available today. Firing tests in existing equipment or the specific development of firing technology in the test centre [3] have proven effective in enabling selection of the most appropriate thermal processing and plant engineering for energy-efficient heat treatment of bulk solids.

References

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