Process Engineering of Metals and Ceramics

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<td>Ceramics</td>
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<td>Ceramics</td>
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Process temperature in °C
Silicate ceramics
- Oxide and non-oxide ceramics
  - Clay bounded SiC
  - Sinter spinel
  - Ferrite ceramics
  - Carbides, Borides, Nitrides
  - Mullit, high alumina products
  - Piezo ceramics
  - Sinter corundum
  - Barium titanate products
  - Chromatic ore stones
  - Abradant
  - Magnesite

Silicate ceramics
- Stoneware
- Vitreous China
- Fine ceramics with heightened $\text{Al}_2\text{O}_3$-content
- Dental-ceramics
- Soft china
- Earthenware
- Silica
- Forsterite
- Bricks
- Clinker
- Refractory

Burning Temperature in °C

Al-forging alloy
- Solution annealing, homogenize
- Recrystallization annealing
- Curing

Al
- Hot forming
- Recrystallization annealing
- Thermally stress relieving

Brass
- Hot forming
- Recrystallization annealing
- Thermally stress relieving

Cu
- Hot forming
- Thermally stress relieving
- Recrystallization annealing

Steel
- Diffusion annealing
- Bright annealing
- Heating for hardening
- Normalize
- Annealing
- Nitrify hardening
- Thermally stress relieving, recrystallization annealing

Heat treatment temperature in °C
Ceramics

Ceramics and its Characteristics

Generally the term 'ceramics' (ceramic products) is used for inorganic materials (with possible some organic content), made up of non-metallic compounds and made permanent by firing process. In addition to clay based materials, today ceramics include a multitude of products with a small fraction of clay or none at all. Ceramics can be glazed or unglazed, porous or vitrified.

Firing of ceramics bodies induces time-temperature transformation of the constituent mineral, usually into mixture of new minerals and glassy phases. Characteristic properties of ceramics products include high strength, wear resistance, long service life, chemical inertness and non-toxicity, resistance to heat and fire, (usually) electrical resistance and sometimes also a specific porosity.

1. Ceramics sectors

The fundamental methods and steps in the production processes hardly differ in the manufacture of the various ceramic products, besides the fact that, for the manufacture of, e.g. wall and floor tiles, table- and ornamentalware (household ceramics), sanitaryware and also technical ceramics, often a multiple stage firing process is used. This is one historical reason why the various ceramics sectors can be summarised in two groups, the group of 'coarse' or 'construction' ceramics including the bricks and roof tiles, vitrifies clay pipes, refractory products and expanded clay aggregates sectors and the group of 'fine' or 'traditional and industrial ceramics', including the wall and floor tiles, table- and ornamentalware, sanitaryware, technical ceramics and inorganic bonded abrasives sectors.

Products of the 'fine' or 'traditional and industrial' ceramic industry differ from products of the 'coarse or construction' ceramic industry in principle in their texture. The border between 'fine' or 'traditional and industrial' and 'coarse' or 'construction' ceramics varies between equivalent particle diameters of 0.1 and 0.2 mm. 'Coarse' or 'construction' ceramic products show an inhomogeneity of more than 0.2 mm but the borderline between 'fine' or 'traditional and industrial' and 'coarse' or 'construction' ceramics is not really fixed today.

1.1 Bricks and roof tiles

Building bricks (e.g. clay blocks, facing bricks, engineering bricks 'clinker bricks', lightweight bricks), roof tiles (e.g. extrcuded tiles, pressed tiles), paving bricks, chimney bricks (e.g. chimney pipes).
1.2 Vitrified clay products

Vitrified clay are used for the pipes and fittings for drains and sews, but also for tanks for acids and products for stables.

1.3 Refractory products

Refractory products are ceramic materials capable of withstanding temperatures above 1500°C. Numerous refractory products in a wide variety of shape and forms are used in many industrial application of steel, iron, cement, lime, glass, ceramic, aluminium, copper and petrochemical industries, in incinerators, power plants, and
house heating systems including night storage heater blocks. They are vital to high
temperature processes and resist all types of stresses (mechanical, thermal,
chemical) such as erosion, creeping deformation, corrosion and thermal shocks.

The resistance of refractory materials to high temperatures is defined so that their
softening point is not less than 1500°C. A classification of 'refractory materials' with a
softening point of between 1500 and 1800°C ad 'high refractory materials' with a
softening point more than 1800°C is commonly used.

1.4 Expanded clay aggregates

Expanded clay aggregates are porous ceramic products with a uniform pore structure
of fine, closed cells and with a densely sintered, firm external skin. They are
manufactured from raw materials containing clay minerals. They are used as loose or
cement bound material for the construction industry (for instance loose fillings,
lightweight concrete, blocks and other prefabricated lightweight concrete components,
structural lightweight concrete for on-side processing) and also loose material in
garden and landscape design (e.g. embankment fillings in road construction,
substrates for green roofs, filter and drainage fillings).

Expanded clay aggregate is used in civil engineering and industrial project as
aggregate of light-weight concrete with volumetric weight 500 kg/m3 and thermal
conductivity 0,13 W/m °C, as heat insulation fillings with thermal conductivity 0,1-0,11
W/m °C, as the bases in road construction and bases in hothouses in plant growing,
in an improvement of private houses, as a filter of polluted by fuel oil and sewer
drains.

Figure 1.3: Expanded clay aggregates
1.5 Wall and floor tiles

Ceramic tiles are thin slabs made from clays and/or other inorganic materials, generally used as coverings for floors and walls. There are several types of ceramic tiles available on the market: shaped through dust pressing or extrusion; with porous, compact or vitrified bodies; with white (whitish) or coloured (reddish) bodies; unglazed or glazed.

![Figure 1.4: Wall and floor tiles](image)

1.6 Table- and ornamental ware (household ceramics)

The manufacture of household ceramics covers tableware, artificial and fancy goods made of porcelain, earthenware and fine stoneware. Typical products are plates, dishes, cups, blowls, jugs and vases.

![Figure 1.5: Porcelain](image)

1.7 Sanitary ware

Ceramic goods used for sanitary purposes are all included under the collective name sanitary ware. Typical sanitary ceramic products are lavatory bowls, bidets, wash basins, cisterns and drinking fountains. These products are mainly made of vitreous china (semi-porcelain) or earthenware.
1.8 Technical ceramics

The European manufacturers of technical ceramics produce a great variety of products, which at least in part are based on clays, but also on synthetic raw materials. Technical ceramics are applied in many industries and cover both, established products like insulators and new applications. They supply elements for the aerospace and automotive industries (engine parts, catalyst carriers), electronics (capacitors, piezo-electrics), biomedical products (bone replacement), environment protection (filters) and many others.
2. Raw Material

Common clay minerals (‘plastic clay’) are hydrated aluminium silicates that have resulted from the weathering of rocks and there are two structural units involved in most clay mineral lattices. One is the 'silica sheet' formed of tetrahedra consisting of a Si$^4+$ surrounded by four oxygen octahedra in which an Al$^{3+}$ ion is surrounded by six hydroxyl groups. These octahedral sheets condense with silica sheets to form the clay minerals.

Formulas (or bodies) of clays based ceramics may consider of one single clay or more clays, mixed with mineral modifiers, so-called 'non-plastics', such as powdered quartz and feldspar.
There are a number of mineral species called clay minerals, but the most important are 'kaolinite', $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$, 'montmorillonite', $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$ and 'halloysite', $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$, 'illite', $\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$, 'bentonite', $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 5\text{H}_2\text{O}$

2.1 Kaolinite: $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$

The kaolinite group includes the dioctahedral minerals kaolinite, dickite, nacrite, and halloysite, and the trioctahedral minerals antigorite, chamosite, chrysotile, and cronstedite. The primary structural unit of this group is a layer composed of one octahedral sheet condensed with one tetrahedral sheet. In the dioctahedral minerals the octahedral site are occupied by aluminum; in the trioctahedral minerals these sites are occupied by magnesium and iron. Kaolinite and halloysite are single-layer structures. Although dickite and nacrite have the same basic structure, the stacking sequence of layers is different in these minerals (Dixon, 1989; Moore and Reynolds, 1997). Kaolinite, dickite, and nacrite occur as plates; halloysite, which can have a single layer of water between its sheets, occurs in a tubular form.
2.2 Halloysite: $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot n\text{H}_2\text{O}$ ($n=0-3$)

2.3 Illite:

$$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O} \text{ or } (\text{K,H}_3\text{O})(\text{Al,Mg,Fe})_2(\text{Si,Al})_4\text{O}_{10}[(\text{OH})_2,(\text{H}_2\text{O})]$$

Illite is essentially a group name for non-expanding, clay-sized, dioctahedral, micaceous minerals. It is structurally similar to muscovite in that its basic unit is a layer composed of two inward-pointing silica tetragonal sheets with a central octahedral sheet. However, illite has on average slightly more Si, Mg, Fe, and water and slightly less tetrahedral Al and interlayer K than muscovite (Bailey, 1980). The weaker interlayer forces caused by fewer interlayer cations in illite also allow for more
variability in the manner of stacking (Grim, 1962). Glauconite is the green iron-rich member of this group.

2.4 Bentonite: $\text{Al}_2\text{O}_3\cdot4\text{SiO}_2\cdot5\text{H}_2\text{O}$

2.5 Montmorillonite: $\text{Al}_2\text{O}_3\cdot4\text{SiO}_2\cdot\text{H}_2\text{O}$

Advanced ceramic products, which contain only a small fraction of clay or none at all, are based on the following materials: Oxide, carbides, nitrides and borides of Al, Mg, Ni, Si, Ti, W, Zr, and other metal ions. Typical examples are $\text{Al}_2\text{O}_3$ (alumina), MgO (perclase or dead burned magnesia), SiC (silicon carbide), TiN (titanium nitride) and WB$_2$ (tungsten boride).
Table 2.1: Analysis of white engobe clays and engobe clays for red roof tiles

<table>
<thead>
<tr>
<th>Chemical analysis, Calcined [%]</th>
<th>White engobe clays</th>
<th>Engobe clays for red roof tiles</th>
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</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>69.7</td>
<td>58.7</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>29.9</td>
<td>20.9</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.0</td>
<td>0.95</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.1</td>
<td>10.4</td>
</tr>
<tr>
<td>CaO</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>MgO</td>
<td>0.4</td>
<td>2.9</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>LOI.</td>
<td>9.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Figure 2.6: Ceramic products and raw materials
The theoretical basis for corundum-spinel products is the MgO- Al₂O₃ phase diagram shown in Fig. 2.7. The compound with the mineralogical name "spinel" is the one in the system MgO- Al₂O₃. It melts at 2135°C, and has a theoretical composition of 71.67 mass% Al₂O₃.

3. Sintering

Sintering is the process of crystals and minerals grow together.

Firing is a key process in the manufacture of ceramic products, as it controls many important properties of the finished ware. These include mechanical strength, abrasion resistance, dimensional stability, resistance to water and chemicals, and fire resistance.

Raw materials used in ceramic bodies are usually complex mixtures of clay minerals, with other mineral matter such as quartz, feldspars, carbonates, gypsum, iron, oxides and sometimes organic matter. Refractory products are also made from a wide range of non-clay mineral, together with specialised additives and binders (which may include some clays). When clay-based ceramic products are fired in a kiln, any moisture is driven off at temperature between 100 and 200°C. If organic matter and iron pyrites are present, oxidation takes place at temperatures of between about 300 and 500°C. Water combined within the structure of clay minerals ('crystal water') is usually released at temperatures of between 500 and 650°C, whilst carbonates such as calcite and dolomite dissociate with the release of carbon dioxide in the temperature range 750 to 950°C.
The most important changes relating to the development of ceramic properties involve the breakdown of the lattice structure of the original clay minerals, followed by the formation of new crystalline compounds and glassy phases. The temperature at which vitrification (glass formation) take place, varies according to the mineralogy of the clay. Vitrification usually commence at about 900°C and is completed by about 1050°C (for many brick clay) or about 1100°C in the case of more refractory fireclays.

During the vitrification stage of ceramic firing, many non-clay minerals such as quartz, oxides or iron, lime compounds and alkalis (oxides of sodium and postassium) become incorporated in the fire body. Some sintering and solid solution occurs, and eutectic reactions take place at the interface of mineral grains and melt phases.

Non-clay products such as some refractory products also depend on sintering, vitrification or recrystallisation stages, but in most cases such higher temperature are required to achieve the desired properties. In the following figure the range of industrial maturing temperatures for different products groups are presented.

Fig. 3.1 shows the micro-structure change in during the sintering process. It shows the structure in microscope at the temperature of 900°C, 1000°C and 1050°C respectively. It can be seen, with the increase of the temperature, the more particles aggregate together, the porosity and the internal surface area decrease with the increase of the temperature.
Figure 3.1: Sintering process in microscope
The in the Fig. 3.1 shown sintering process is described with schematic diagram in Fig. 3.2. It can be seen, with the increase of the time and temperature, two particles aggregate together. The higher the temperature, the more contact area of the particle.

![Schematic sintering process in microscope](image)

**Figure 3.2:** Schematic sintering process in microscope

Fig. 3.3 shows the change of the green product density and internal surface with the firing temperature. According to the above description, it is clear, that with the increase of temperature and time, the internal surface decreases. For the green product density, it decreases at first because of the volume extension. After 900°C, because of the firing shrinkage, the density increase again.

![Density and internal surface changes with temperature](image)

**Figure 3.3:** Density and internal surface changes with temperature

When the green product volume during the sintering process is discussed, it increases slightly at first. Then from 600°C~1000°C, significant volume extension happens. After that, above 900°C, significant firing shrinkage will take place, this will become very intensive after the temperature increase. Fig. 3.4 shows this series of volume change.
Fig. 3.5 shows the cracks on the bricks, when the temperature is between 700°C~900°C. As already explained in Fig. 3.4, in the temperature range of 600°C~1000°C, there is a volume extension, therefore, cracks may appear in this temperature range. To investigate the volume change during the firing process is meaningful, to avoid the crack of the brick and deformation of the other ceramics like porcelain and sanitary ware.

Table 3.1 shows the firing temperature for different products. It can be seen, for the bricks and clinker, the firing temperature is only 1000°C~1150°C, while for the
porcelain and refractory, the temperature is much higher. This is because, for the porcelain and refractory, the porosity inside is much lower, therefore, higher firing temperature is needed.

**Table 3.1:** Firing temperature

<table>
<thead>
<tr>
<th>Product</th>
<th>Temperature in °C</th>
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<tbody>
<tr>
<td>Refractory</td>
<td>1400~2000</td>
</tr>
<tr>
<td>Brick</td>
<td>1000~1050</td>
</tr>
<tr>
<td>Clinker</td>
<td>1100~1150</td>
</tr>
<tr>
<td>Vitrified clay</td>
<td>1200~1300</td>
</tr>
<tr>
<td>Stone ware biscuit firing</td>
<td>1220~1280</td>
</tr>
<tr>
<td>Stone ware glaze firing</td>
<td>1100~1180</td>
</tr>
<tr>
<td>Porcelain biscuit firing</td>
<td>900~1000</td>
</tr>
<tr>
<td>Porcelain glaze firing</td>
<td>1400~1420</td>
</tr>
<tr>
<td>Porcelain decoration firing</td>
<td>700~1400</td>
</tr>
<tr>
<td>Sanitary ware</td>
<td>1300~1350</td>
</tr>
</tbody>
</table>

The firing temperature for different products are shown again in the Fig. 3.6.

**Figure 3.6:** Firing temperature for different products
4. Production Process

The main steps in the manufacture of ceramic products are largely independent of the materials used and the final product. The following figure schematically shows the typical process and possible or necessary supply and disposal facilities. The process is made up of the steps: mining/quarrying of materials and transport to the ceramic plant, storage of the raw materials, preparation of the raw materials, shaping, drying, surface treatment, firing and subsequent treatment.
Figure 4.1: General production process
4.1 Production Process of Brick and Roof Tile

The manufacture of bricks and roof tile goes through the stages of mining/quarrying of raw materials, storage of raw materials, raw materials preparation, mixing and kneading, shaping, drying, firing, subsequent treatment. Special requirements for the surface and colour of the products involve a surface treatment by glazing, engobing or profiling. The following figure shows, as an example, a schematic view of the manufacture process of brick and pressed roof tile.

4.1.1 Raw material preparation

The manufacturing of brick begins with the gathering of surface clay and shale from the quarry. Raw materials are transported to storage areas in preparation for crushing. The crusher breaks up the large chunks of clay or shale and passes it to conveyors leading to the grinders. The grinders pulverize the material to fine material. The pulverized material passes over a vibrating screen in which the fine material passes through to the next step and the coarse material is returned to the grinder to be reground again.

4.1.2 Mixing and Kneading

Up to this point the material has been kept dry. Here in this step, water is added to provide the proper plasticity and preparing for shaping. For different shaping process, different amount of water will be added, they are shown as follows:

- 20~25% mass referenced water for pressing,
- 25~30% mass referenced water for extrusion,
- 30~40% mass referenced water for casting in molds.

Due to the density different of the water and minerals, $\rho_{\text{water}}=1\text{g/cm}^3$ while $\rho_{\text{minerals}}=2.2~3\text{g/cm}^3$, the volume fraction of water is 2.2~3 times higher than the mass fraction of water.

Materials such as manganese are added to change the body color for the bricks which special colors a required, and other special waste, like contaminated wood, ash from coal firings, styropar, sewage sludge, waste mineral wool and so on, are added to assure the required high special porosity.

4.1.3 Shaping

The next step is to make the material into the shape of the brick. There are three basic methods that can be used to shape the material: handmade, machine molded or extruded. Each method imparts a different look to suit the character and personal taste of the customers.

In the handmade method, a soft mixture is forced through an extruder, cut into slugs and conveyed to work stations. The slugs are then individually picked up, rolled in
sand and thrown into a pre-sanded wooden mold by a worker. Excess raw material is removed by a wire and endless belt. As the filled mold boxes continue on their journey, they are mechanically bumped on their ends to loosen the brick from the mold prior to dumping.

Machine molded brick are made from shale or clay material that is pugged or mixed with considerable water and placed in a machine that presses the wet mix into molds previously sanded. The mold boxes are then bumped and dumped. A variety of sands are used to keep the brick from sticking in the molds and to affect different textures and colors of the final product.

![Figure 4.2: clay in mold boxes and dumping mold box](image1)

The shale and clay materials for extruded brick are mixed with a moderate amount of water. This mixture is forced by means of an auger through a die having the shape of the brick. Prior to entering the die, the material passes through a vacuum changer that reduces the amount of air in the mix resulting in a denser, more homogeneous product. It is here that core holes are placed in the column. The core holes are needed to reduce the mass for firing and the weight for future handling. The column that is produced by the extruder is cut by wires to make individual brick. Scratching, scraping, rolling or sanding the surface of the column as it exits the die produce multiple textures on the face of the brick.

![Figure 4.2: extruder and core hole die on extruder](image2)
4.1.4 Setting

After the green brick is formed using any of the methods described above, the green bricks are hand or mechanically set onto kiln cars. The setting of the green bricks is extremely important for the energy consumption of firing. A lot of scientific researches have been made for investigating the optimal setting to increase the heat transfer and decrease the flow pressure drop.
4.1.5 Drying, glazing and engobing

Before entering into the tunnel kiln, the unfired or green brick must be properly dried. This is a very important part of the brick manufacturing process. Generally, the drying process is done by placing the green brick in enclosed dryers. During the first drying period, the green products will be shrunk, therefore, improperly drying will induce the occurrence of the cracks inside of the green bricks and other mechanical defects. Some special drying devices can realize the soft drying, which will avoid these phenomenon. Due to the high vaporization enthalpy of water, vaporization of the moisture needs a high amount of energy. In most of the production cases, the energy for the green bricks drying comes from the excess heat of the hot cooling gas, which is blown from the end of the tunnel kiln, after increasing the temperature, finally is transported out of the tunnel kiln from the transient position between firing zone and cooling zone. After drying, the green bricks contain 1-3% mass referenced water.

Roof tiles and facing bricks are sometimes glazed and engobed on the visible surface or on the whole surface to achieve special colors or to increase the density of the product. Glaze and engobe are applied to the body after the drying process. In some cases, glazing and engobing is carried out after the shaping process. Engobe is a composition made of clay, fluxing agents, filling material and pigments. The best
process to apply larger quantities to the ware is by spraying. Organic binding agents are added to the engobe to achieve a better binding between the fluid engobe and the treated surface. Glaze is a mixture of batch material, fluxing agents, clay and colouring oxides, which are sintered to a vitreous mass. The glaze is usually applied by spraying in a spray chamber.

4.1.6 Firing

The next step is burning or firing the green brick. The green brick pass through the long tunnel kiln on a continuous procession of cars moving on rails, much like a small railroad train. The continuous tunnel kiln employs a combination of vertical and horizontal drafts. The preheating, firing and cooling is done in zones varying in temperatures up to 2000°C. In the general brick production, the firing temperature is between 950°C-1050°C. In this type of kiln, closer and more accurate temperature control is possible and easily handling of the green brick can assure the better products quality.

4.1.7 Packaging, Subsequent treatment

After exiting the kiln, the brick is allowed to cool prior to handling. Proper sorting ("dehacking") and packaging of the brick after burning is extremely important. Broken, twisted and otherwise mechanically defective brick are discarded at this stage. Brick color and range is carefully monitored to assure a quality product. The finished product is packaged and banded into cubes of approximately 500 brick, inventoried by lots and distributed to customers.
Figure 4.6: Packaging and subsequent treatment
4.2 Production Process of Porcelain

The process of porcelain is made up of the following steps: storage of the raw materials, preparation of raw materials, shaping, drying, firing, glazing, decoration and subsequent treatment. The following figure shows the stages of the manufacture of table porcelain.
4.2.1 Preparation of raw materials

The preparation of raw materials for the manufacture of porcelain is performed in a wet or a dry process. 'Extrusion paste' and 'dust pressing powder' are predominantly produced. Body components are mainly metered gravimetrically. If kaolin compounds are dissolved in water, volumetric apportioning also takes place. In general, glazing raw materials are dosed gravimetrically. The plastic body compounds are suspended in water in stirred tanks to prepare the compounds for the mixing process. The
following wet milling is performed in drum mills or in stirrer mills. Hard body compounds are often delivered with the correct particle parameters, so that no additional milling is necessary. Plastic body compounds and hard body compounds are mixed in stirrers or mixers. The compounds are screened to remove impurities followed by deferrisation which removes foreign iron compounds. Deferrisation is performed in electromagnetic fields. The body slip is dewatered mechanically in filter presses or thermally in spray dryers. For the production of 'extrusion paste', the water content of the slip is reduced from 65 % down to 20 to 25 % in filter presses or in rotation filters. The filter cake is homogenised and formed into clots in extrusion presses. For the production of 'dust pressing powder', the slip cast is dewatered down to 5 to 8 % water content in spray dryers. The slip cast is pumped into the spray dryer by a special slip cast pump. The water content is reduced by a hot gas stream. The flue-gas of the gas heated dryer and the vaporised water leave the dryer at the top.

Organic slip additives and binding agents are added to the 'dust pressing powder' to achieve soft and slide characteristics of the powder. Carboxymethyl cellulose, methyl cellulose, cellulose ether, polyvinyl alcohol, polyvinyl acetate and polysaccharide are used for this purpose. Olein, mineral oil, stearic acid and wax are added. The share of slip additives and binding agents in the 'dust pressing powder' is between 0.2 and 0.4 wt-%. 'Dust pressing powder' produced in the fluidised bed process can be used with a reduced share of slip additives and binding agents thus providing better deformation characteristics.

Fluidised bed granulation on the one hand and non-thermal granulation processes on the other hand, are future alternatives in the production of 'dust pressing powder'. The specific energy consumption of fluidised bed granulation is higher than in the normal spray drying process but the specific thermal energy consumption is lower.

If 'extrusion paste' for soft plastic shaping is produced by the use of 'dust pressing powder', the powder and returning slip cast is mixed until the water content is about 20 to 25 %. The extruded cylindrical sections are stored for some time to guarantee even moistness and tension. Organic additives and agents and inorganic binding agents such as magnesium chloride, magnesium sulphate, phosphate or borax are used to increase the strength of the plastic compounds for soft-plastic shaping.

Filter cake, waste from plastic compounds for hard-plastic shaping or 'dust pressing powder' are dissolved in water to produce casting compounds (casting slip). The water content of the casting slip is between 25 and 35 %. To ensure a good slip characteristic, even with lower water contents, additives such as soda, sodium or potassium silicate, caustic or humic acid are used.

### 4.2.2 Shaping

There are three different types of shaping processes in the manufacture of household ceramics. Flatware such as plates and dishes are predominantly manufactured in the dry pressing process. Hollow wares, e.g. vases, are manufactured in the casting process, while cups and jugs are manufactured in the plastic shaping process.
In the dry pressing process, 'dust pressing powder' (water content of around 5 %) is pressed isostatically with auxiliary agents. The 'dust pressing powder' is filled into a press. The press consists of an upper and a lower part. In the lower part, the isostatic membrane works as the main part of compression. Depending on the product, the upper part of the press is designed in various shapes. Horizontal presses using multi-form heads are able to produce various products with a high output. Double head presses produce up to 1200 pieces per hour. The powder is pressed into the form with a pressure of 30 MPa. The advantage of this process is the low water content of the green ware.

In the plastic shaping process, the ‘extrusion paste’ (water content of between 20 and 25 %) is formed in jiggering machines with the aid of profile tools. Dynamically balanced goods are produced in plaster moulds, which are manufactured in special facilities. The cylindrical plastic body is cut in similar slices. In the next step, the slices are mechanically apportioned to the plaster moulds of the jiggering machines. The lifetime of the plaster moulds is very short. Plaster moulds are often used for only a 100 to 150 pieces. Recently, porous moulds made of polymer materials have been employed to achieve a longer lifetime.

Non-dynamically balanced goods are produced in the slip casting process. Body formation takes place by dewatering the slip cast in plaster moulds. The solid casting process is used mainly for the production of flatware. Vases and jugs are manufactured in the drain casting process. Casting machines are used for manufacture on an industrial scale. Production on a small scale is carried out by hand-casting. The body formation time can be reduced under pressure. Pressure casting takes place in porous polymer moulds under pressures of up to 4 MPa. Pressure casting is much faster than the conventional casting process, so that the casting cycles last for two or three minutes only.

Plastic pressing is an additional process used for the manufacture of household ceramics. Goods are manufactured in two-part plaster moulds or polymer moulds. Compared with the slip casting process by using a plastic body, this process reduces the body formation time considerably.

### 4.2.3 Drying

Goods produced in the slip casting process or in the plastic shaping process have to be dried in special dryers to a water content of less than two per cent. Chamber and tunnel dryers heated with kiln waste heat, natural gas or fuel oil EL is used for this dewatering. Infrared dryers and microwave dryers are an alternative to the conventional drying process. These dryers are employed for the pre-drying of the casting compounds and also for the drying of used and new plaster moulds. Microwave dryers are built as chamber, tunnel and chamber-passage dryers.

Surface roughness and mould marks resulting from the shaping process are removed in the dressing process. Dressing is carried out with knives and by subsequent treatment with a wet sponge rubber. Pressed and jiggered goods are cleaned predominantly by machines, other goods are treated manually. For manufacturing on an industrial scale, the shaping, drying and dressing processes are united in one stage of manufacture.
4.2.4 Firing, glazing and decoration

Porcelain are fired between one and four times, depending on the material and the production technique. In the first step, biscuit firing gives the semi-product the strength and absorbency needed for the glazing. Biscuit firing temperatures are between 900 and 1050 °C, the firing time in classic tunnel kilns is between 18 and 30 hours. Fast firing kilns achieve firing times of between three and seven hours.

Glazing follows biscuit firing. The glaze consists of glassy compounds with a higher share of fluxing agents dispersed in water. Hollow goods (except for cups) are glazed by manual dipping. Flatware and cups are glazed mechanically in a pouring-glazing process, whereas small scale production is glazed manually by dipping. Flatware is also glazed by spraying. Adhesive agents (for example polyamine or dextrine) are used as organic binding agents and glues. Electrolytes are mixed with the glaze to achieve faster drying.

The glost firing that follows is performed in an oxidising or reducing atmosphere at temperatures of between 1320 and 1430 °C. Glost firing kilns are tunnel kilns with tunnel kiln cars, (multi-rack) roller hearth kilns, fast firing tunnel kilns with moving firing tables, slab kilns or belt conveyer kilns. Periodic kilns such as chamber kilns, shuttle kilns and hood-type kilns are operated at lower feed rates. The ware to be fired is set on fireproof firing auxiliaries (so called 'kiln furniture'). Glost firing time varies between 25 and 36 hours in the tunnel kiln and between three and a half and five hours in fast-firing kilns without firing auxiliaries.

Table 4.1: Operating data of tunnel kiln

<table>
<thead>
<tr>
<th>Tunnel kilns</th>
<th>Unit</th>
<th>Porcelain</th>
<th>Porcelain</th>
<th>Porcelain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firing</td>
<td>Biscuit</td>
<td>Glost</td>
<td>Glost fast</td>
<td>Glost fast</td>
</tr>
<tr>
<td>Throughput</td>
<td>t/h</td>
<td>0.3 – 0.7</td>
<td>0.2 – 0.4</td>
<td>0.58</td>
</tr>
<tr>
<td>Kiln length</td>
<td>m</td>
<td>60 – 100</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Cross-section</td>
<td>m²</td>
<td>0.5 – 1.0</td>
<td>0.5 – 1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Setting density</td>
<td>kg/m³</td>
<td>60 – 70</td>
<td>60 – 70</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Firing temperature</td>
<td>°C</td>
<td>850 – 1260</td>
<td>1200 – 1400</td>
<td>1420</td>
</tr>
<tr>
<td>Specific energy</td>
<td>kJ/kg</td>
<td>25,000</td>
<td>20,000</td>
<td>12,500</td>
</tr>
<tr>
<td>requirement (drying + firing)</td>
<td></td>
<td></td>
<td></td>
<td>without drying</td>
</tr>
<tr>
<td>Flue-gas volume flow</td>
<td>m³/h</td>
<td>3500 – 5000</td>
<td>3500 – 5000</td>
<td>n.a.</td>
</tr>
<tr>
<td>Flue-gas temperature</td>
<td>°C</td>
<td>120 – 170</td>
<td>120 – 170</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

The glaze melts during the firing process and seals the porous ceramic body. The surface becomes watertight and smooth. After the glost firing, the goods are divided into corresponding quality grades. Areas with no glaze are ground and polished to maximise the value of the products.

Bone china is a speciality for traditional tableware and tea services. Important raw materials for bone china are Cornish clay, Cornish stone and up to 50 % calcined bovine bones. The gloss firing temperatures are between 1250 and 1350 °C, and biscuit firing temperatures are between 1100 and 1150 °C. A kiln atmosphere with glaze vapour ensures a very smooth surface.
The decoration process which follows, maximises the value of the product and permits customisation. On-glaze colours, in-glaze colours, under-glaze colours and metal compounds are used for the decoration. In the on-glaze decoration process, glazed and already fired goods are decorated. On-glaze decoration is melted into the glaze by an additional firing process. In the in-glaze decoration process, the coloured pigments sink into the glaze. In the under-glaze decoration process, the goods are decorated before the glazing process starts. Typical decoration processes are the slide-off transfer, reprinting, direct silk screen printing, offset printing, lining, banding, stamping, powdering, painting, spraying, stencilling and etching. Besides manual decoration, machines for silk screen printing and coloured printing are employed. Numerous oxides are set in as fluxing agents, opacifiers and for direct colouring in the glazing and decoration processes. The glaze and decoration colours consist of complex systems of numerous pigments. In the following list, the elements and their chemical valence (in brackets), in which they appear as oxide compounds in the pigments, are mentioned: Cu (1, 2), Ca (2), Zn (2), Al (3), In (3), Si (4), Sn (4), Pb (2), Ti (3, 4), Zr (4), Ce (4), Pr (4), V (4, 5), Sb (3, 4, 5), Cr (3, 6), Mo (4, 6), Mn (2, 4), Fe (2, 3), Co (2), Ni (2) und Cd (2).

4.2.5 Subsequent treatment

After decoration and quality control, the products are sorted. The wet subsequent treatment is carried out by grinding and polishing machines to smooth the surface of the products. Certain products are pre-packed mechanically. Then the sets for sale and dispatch are put together and manually packed. For the manufacture of modern tableware, semi-products are handled automatically by robots between the shaping, drying, firing and subsequent treatment stages.

5. Tunnel Kiln

Tunnel kiln is a long kiln, which looks like a tunnel and is made of the refractory and heat insulated construction materials. Inside of the kiln, there are some kiln cars to transport the green products and the final products. It is mainly used for producing the ceramic products, such as brick, tile, sanitary wares, porcelain and so on.

During the operation of the tunnel kiln, the pre-treated green products are loaded on the kiln car, they enter to the kiln with the kiln car from one side of the kiln, after the increase of the temperature and undergoing the sintering, the green products will become the products and then, they will move out of the kiln from the other side. After the remove all the products, the empty kiln car will go the other side of the kiln, to begin the next production cycle.
Figure 5.1: Schematic diagram of tunnel kiln

Figure 5.2: Tunnel kiln overview

Figure 5.3: Schematic diagram of whole tunnel kiln system
Tunnel kiln is a counter flow heat exchanger, that is to say, the solid on the kiln cars move continually in the reverse direction of the gas direction in the kiln. This is shown in Fig. 5.4, in which the arrows show the flow direction of the goods and gas.

**5.1 Zones of tunnel kiln**

There are three zones in the tunnel kiln: preheating zone, firing zone and cooling zone. No critical physical boundaries exist for the zones, but there are some geometric boundaries and criteria (three discussed following) to distinguish of the different zones for the scientific research.

According to the **length**:
- Preheating zone: 30-45% of the total length
- Firing zone: 10-33% of the total length
- Cooling zone: 38-46% of the total length

According to the **temperature**:
- Temperature in reheating zone: from environment temperature to 950°C
- Temperature in the sintering zone: from 950°C to the highest temperature
- Temperature in the cooling zone: from the highest temperature to the temperature when the products come out of the kiln

According to the **position of the combustion chamber** (commonly used)

**5.1.1 Preheating zone**

During this process, the green products contact the flue gas coming from the firing zone, the temperature of the green products will increased gradually, so that finish the preheating process.
From the ambient temperature to 100-120°C, the moisture in the green products will come out, and the temperature of the green products will be gradually increased.

From 300°C to 500°C if organic matter and iron pyrites are present, oxidation takes place.

From 500°C to 650°C water combined within the structure of clay minerals ('crystal water') is usually released.

From 600°C to 800°C fixed carbon in carbonates such as calcite and dolomite dissociate with the release of carbon dioxide.

- \( \text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaO} + \text{MgO} + 2\text{CO}_2 \uparrow \) from 600°C to 700°C
- \( \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \uparrow \) from 750°C to 800°C

Big problem in this process is the deformations of the green products. Fig. 3.4 shows the extension and shrinkage for the different product groups in the different temperature range during the bricks production. It shows for all the curves, they have the same change tendency as following described:

1. The thermal extension begins immediately after the green products enter into the preheating zone.

2. Above 450°C there is a progressive curve increase.

3. The clear anomaly form step in the 573°C comes from the spontaneous transformation of the free quartz taking place here, from low temperature into the high temperature (quartz spring).

4. In the range of 600 to 900°C, there is no significant extension or shrinkage. Here the thermal extension will be compensated by the solid reaction.

5. Above 900°C, significant firing shrinkage will take place, this will become very intensive after the temperature increase.

5.1.2 Firing Zone

Green products will be sintered using the heat generated by the combustion of the fuel, the required highest temperature will be reached, and in this zone, the green products will be finished the sintering process and transferred to the products with high temperature.

From 950°C to 1300°C is sintering and high temperature keeping stage. There are solid phase reactions. This is the most important changes relating to the development of ceramic properties involve the breakdown of the lattice structure of the original clay minerals, followed by the formation of new crystalline compounds and glassy phases. Shrinkage will take place in this stage because of the structure transformation. The final products in this stage are glasses, rock stone and quartz grains.
5.1.3 Cooling zone

The products with high firing temperature go in to the cooling zone, they are cooled by the lower temperate air blowed from the end side of the tunnel kiln, which plays the function of a counter flowed heat exchanger. The temperature of the products will decrease.

From 1300°C to 700°C is **rapid cooling stage**, so that the glass phase can be kept, and avoid the low-valency **Fe** to be oxidized. This can make the products have vanish, half-transparence and white surfaces (in ceramic production).

From 700°C to 400°C is **static cooling stage**, to avoid the cracks of the products because of the changes of the crystal construction.

From 400°C to the products output temperature is **final cooling stage**, to increase the production speed and improve the productivity.

5.2 Gas Control

A gas control system exits in the tunnel kiln. Fig. 5.5 shows this system.

![Figure 5.5: Gas control system in tunnel kiln](image)

5.2.1 Cooling Air

A great amount low temperature air will be blown into the tunnel kiln from the end of the kiln. After the heating of the air, one part of the air is blown into the sintering zone, as the diffusion air to help the combustion of the fuel; the other part of the high temperature air will be transported to drying the green products. According to the
above discussed cooling process, the cooling air should also have there types: rapid cooling gas, static cooling gas, and final cooling gas.

5.2.2 Flue Gas

The combustion gases generated in the firing zone will be bowed to the preheating zone along the inside channel of the kiln, after preheating the green products, the flue gas will be cooled, and will be vented from the main and sub flues and chimneys in the preheating zone. Due to the organic components in the gas, the flue gas will be cleaned before it emitted into environment.

5.2.3 Gas curtain

There are some air curtains in the different positions in the tunnel kiln. air curtain means from the top or both sides of the kiln wall, air is injected into the kiln to become a curtain in the cross section. Generally speaking, there are four types of air curtains in the different positions in the tunnel kiln, their functions and requirements are different.

At the beginning of the kiln - **Sealing air curtain**. the purpose of the sealing air curtain is keeping 1~2 Pa positive pressure at the beginning of the kiln, to avoid the cold air entering into the kiln. Usually there are two layers of air curtains here, the first layer curtain is cold air, the second curtain is hot air, coming from the cooling zone. From the top and both sides of the kiln, air is injected with a certain velocity. This velocity is vertical to the direction of the car movement.

In the preheating zone - **perturbation air curtain**. There are 2~3 gas curtains, in order to avoid the formation of different gas levels. The pressure in the preheating zone is negative, so it is easy for the cold air outside of the kiln to enter the kiln. Because of the high density, the cold air sinks on the bottom of the kiln, while the hot gas will stay on the bottom of the kiln, therefore it forms different gas levels. This makes the different of the gas temperature between the top and bottom is maximum up to 300~400°C. This will prolong the preheating time, which means the green products on the bottom have to be waited until they reach the high temperature completely. Therefore the productivity is decreased, and the fuel consumption is increased.

A certain amount of hot air can be injected into the tunnel kiln from a row of nozzles on the kiln ceiling, with relative high velocity and a certain angle. It forces the hot air to flow to the bottom of the kiln, making the temperature in the kiln uniform. The direction of the injection should be vertical to kiln bottom, or with a certain angle, which reverses to the flue gas direction.

The temperature of the air curtain should be the same as the gas temperature in the cross section, otherwise it makes the decrease of the local temperature, some cracks in the products will appear. The hot gas for the perturbation air curtains comes from the flue gas from the sintering zone or the hot gas from the cooling. The injection velocity is more than 10m/s. There are some tunnel kilns with the high velocity air injection more than 100m/s, it makes intensive perturbation in the kiln, the
temperature between the top and bottom is uniform, and the preheating time is very short. The injection angle can be 90° vertical to the bottom, but it can also vary from 120° to 180°.

There are also circulation air curtains in the preheating zone. Through blowers or injection pumps, the gas inside of the kiln will be circulated, in order to realize the homogenous temperature.

In the sintering zone - oxidizing air curtain. Hot gas is injected into the kiln, at the position where the temperature between 950°C to 1050°C will meet the flue gas containing carbon monoxide and reacts completely. Here enough amount should be assured, air access number should be between 1.5-2.0, but the air can not be too much, in order to avoid the incomplete oxidize reaction due to the too low local temperature, which will form bubbles inside of the products. The hot air comes from the cooling air, or some hot gas in the sintering zone.

At the beginning of the cooling zone - block air curtain. The green products should be cooled rapidly after sintering and before they reaches 700°C, so that increase the product quality and shorter the production time. The block air curtain avoid the flue gas in the sintering zone flowing back to the cooling zone. This makes, on the one hand, rapid cooling will not be influenced by the hot gas from the sintering zone; on the other hand, the dirty flue gas from the sintering zone can not contact the products. The operation of the block air curtain is similar with the sealing air curtain.

5.3 Sealing systems of the tunnel kiln

Due to the high temperature, the kiln should be well insulated to avoid the heat loss from the kiln wall to the ambient and the heat loss from the kiln car to the earth. Fig. 5.6 show the cross section of the kiln to avoid the above mentioned heat losses.

![Cross section of the tunnel kiln](image)
Kiln wall is one of the main parts of the tunnel kiln. Fig. 5.6 illustrates that the roof can be built either soffit or flat. The kiln wall is consists of three working layers: refractory layer contact the fire directly, fire light bricks are in the middle of the kiln wall, and insulation layer reserve the heat. In the industry, there are also other layers made of the kiln wall, such as protect layer, seal layer and so on. The choose of the wall materials are dependent on the wall material properties, insulation, heat conservation and material cost.

The labyrinth-sealing and sandrine are also shown in Fig. 5.6, they avoid the heat loss from the kiln car to the earth.

5.4 Sanitary Ware
Fig. 1-14

- Refractory lining
- Burner
- Load
- Role with drive
- Flue gas
- Fuel
- Air
Innovative Neuerungen

Doppelspurofen
6. Tunnel kiln calculation (Design of kiln)

As discussed above, tunnel kiln can be simplified as counter-current heat exchanger. The temperature profile and movement direction of solid and gas in the preheating and firing zone can be shown in Fig. 6.1. In this figure, the temperature difference between the surface and core of the solid is shown. It is illustrated the gas flows from the firing zone to preheating zone, the gas temperature decreases gradually. For the solid, it moves in the reverse direction, from preheating zone to firing zone. The solid surface temperature increases rapidly at first, when the solid just goes into the kiln, then it increases slowly; while the solid core temperature remains constant at first, and then it increase with the increase of the surface temperature. In the firing zone, the surface and core temperatures are almost the same, they are the firing temperature.
6.1 Specific energy consumption

For the calculation of the specific energy consumption, mass and energy balance for the preheating zone and firing zone are set. Fig. 6.2 shows the mass balance. For the analysis, the combustion chamber and kiln are defined as a whole system. The system inputs are fuel, combustion air and the incoming solid, while the outputs are outgoing solid and the flue gas. For the convenience of calculation, the solid temperature profile shown in Fig. 6.1 can be simplified as shown in Fig. 6.2, where the mean solid temperature of is used.
According to the mass balance described in Fig. 6.2, the energy balance for the system can be expressed as:

\[ M_L \cdot h_u + M_L \cdot c_{PL} \cdot T_L + \dot{Q}_{\text{solid, in}} = \dot{Q}_{\text{solid, out}} + M_G \cdot c_{PG} \cdot T_A \]  

(6-1)

where \( \dot{Q}_w \) is heat flow of loss from the kiln wall to the environment.

The incoming solid consists of green products and the transportation medium (for example, kiln car and kiln furniture etc.), it can be expressed as:

\[ \dot{Q}_{\text{solid, in}} = M_S \cdot c_S \cdot T_{S,in} + M_T \cdot c_{ST} \cdot T_{S,in} \]  

(6-2)

and so does the outgoing solid

\[ \dot{Q}_{\text{solid, out}} = M_S \cdot c_S \cdot T_{S,out} + M_T \cdot c_{ST} \cdot T_{S,out} \]  

(6-3)

According to the experience, the thermal mass of the transportation medium can be expressed as the thermal mass ratio between the transportation medium and the product. This value varies from the production process and the products, generally between 0.3 ~ 1.5.

\[ \frac{M_T}{M_S} = 0.3 \sim 1.5 \]  

(6-4)

For the brick production, only kiln car is needed, therefore, \( \frac{M_T}{M_S} \) is relatively smaller, which is approximately 0.3, while for the porcelain or some sanitary ware, because a large number of kiln furniture are required for the stability, \( \frac{M_T}{M_S} \) is relatively higher, up to 1~1.5.

The in the Eq (6-1) expressed mean specific heat capacity of flue gas \( c_{PG} \) is temperature dependent. To calculate this, the specific heat capacity for gas component should be determined. With the definition of the enthalpy, a mean value must be introduced in the balance between the air and gas temperatures

\[ \Delta h_{LG} = \int_{T_L}^{T_G} c_p(T) \cdot dT = c_{PG} \cdot (T_G - T_L) \]  

(6-5)

Consequently the mean specific heat capacity of flue gas \( c_{PG} \) can be expressed as:

\[ c_{PG} = \frac{\int_{T_L}^{T_G} c_p(T) \cdot dT}{T_G - T_L} \]  

(6-6)
The temperature dependence of the specific heat capacity of a gas component can in fact be approximated very well by the power function

\[ c_{pG}(T) = c_p(T_0) \cdot \left( \frac{T}{T_0} \right)^n \]  

(6-7)

Thus the following results as the mean value of a gas component

\[ \frac{c_p(T)}{c_p(T_0)} = \frac{1}{n+1} \cdot \frac{(T/T_0)^{n+1} - 1}{T/T_0 - 1} \]  

(6-8)

For different gas component, the exponent index \( n \) is different, which are shown in Table 6.1.

<table>
<thead>
<tr>
<th>gas</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(_2)</td>
<td>0.11</td>
</tr>
<tr>
<td>O(_2)</td>
<td>0.15</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.30</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>0.20</td>
</tr>
</tbody>
</table>

The mean specific heat capacity of the gas mixture is obtained from sum of the mass related specific heat capacity of the individual components

\[ c_{pG} = \sum c_{pi} \cdot x_i \]  

(6-9)

\( x_i \) is the mass concentration of CO\(_2\), H\(_2\)O, O\(_2\), N\(_2\).

The following applies to the mass flows, for the mass of the combustion air

\[ \dot{M}_L = \dot{M}_i \cdot L \cdot \lambda \]  

(6-10)

and the mass of the flue gas

\[ \dot{M}_G = \dot{M}_i + \dot{M}_L = (1 + \lambda \cdot L) \cdot \dot{M}_i \]  

(6-11)

From the energy balance (6-1) and the above explained equations, the specific energy consumption can be obtained

\[ E = \frac{\dot{M}_i \cdot h_u}{M_S} = \frac{c_s + c_{ST} \cdot \dot{M}_i / M_S}{1 - (1 + \lambda \cdot L) \cdot c_{pA} \cdot (T_A - T_L) / h_u} \cdot (T_{S,\text{out}} - T_{S,\text{in}}) + \dot{Q}_w / \dot{M}_S \]  

(6-12)

If the air is only slightly preheated, then the enthalpy of the air \( \lambda \cdot L \cdot c_{pL} \cdot T_L \) is only approximately 1 to 3 % of the heating value.
\[ \lambda \cdot L \cdot c_{pL} \approx (1 + \lambda \cdot L) \cdot c_{pA} \]  \hspace{1cm} (6-13)

can be approximately set.

For natural gas, the air demand is \( L \approx 15 \).

From the Eq. (6-12), it indicates that \( E \) is proportional to \( T_{S,\text{out}} - T_{S,\text{in}} \), that is to say, the higher the firing temperature \( T_{\text{firing}} \), the higher energy requirement \( E \).

Another, it also illustrates \( E \sim \dot{Q}_w / \dot{M}_w \), which means kiln should have good insulation, to lower the energy loss from the kiln wall to the environment. Currently, the energy loss from the kiln wall is 0.05-0.1MJ/kg.

Thirdly, \( E \sim c_{ST} \cdot \frac{\dot{M}_L}{\dot{M}_g} \). This tells kiln furniture should have high porosity so that the thermal mass of the kiln furniture is low.

Finally, in order to reduce the energy requirement, flue gas temperature \( T_A \) must be as low as possible. However, \( T_A \) must be higher than the condensation temperature of \( \text{SO}_2 \). Because of the sulfur from the fuel and some raw materials likes clay loam, during the firing process, sulfur acid is produced

\[
\text{SO}_2 + \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{SO}_4
\]

The flue gas contained sulfur acid must be washed out, before it emitted into the environment.

### 6.2 For assessment of process efficiency

Firing efficiency is defined as

\[
\eta_f = \frac{\dot{Q}_{\text{solid}} + \dot{Q}_{\text{loss}}}{M_i \cdot h_u} = 1 - \frac{(1 + \lambda \cdot L) \cdot c_{pA} \cdot (T_A - T_i)}{h_u} \hspace{1cm} (6-14)
\]

it is known, the lower the air access number \( \lambda \) is, the lower the flue gas temperature \( T_A \) is, and the higher the firing efficiency. To determine the air access number \( \lambda \), the flue gas can be analyzed, the concentration of different components like \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) can be measured.

The efficiency of the kiln process can be defined as:

\[
\eta_a = \frac{\dot{Q}_{\text{solid}}}{\dot{Q}_{\text{solid}} + \dot{Q}_{\text{loss}}} \hspace{1cm} (6-15)
\]

where
\( \dot{Q}_{\text{solid}} = \dot{Q}_{\text{solid, out}} - \dot{Q}_{\text{solid, in}} \) \hspace{1cm} (6-16)

and the total efficiency of the process is

\[ \eta_{\text{total}} = \eta_f \cdot \eta_s \] \hspace{1cm} (6-17)

To calculate with Eq.(6-14), for the existing kiln, heating value \( \dot{M} \) of the fuel can be measured, specific energy requirement \( E \) is known, air access number \( \lambda \) can be measured from the flue gas composition, flue gas temperature \( T_A \) can be calculated and checked with measurement.

For the new kiln design, however, the air access number \( \lambda \) and flue gas temperature \( T_A \) are unknown. They are dependent on the heat transfer and the geometry of the kiln. Therefore, the calculation for the flue gas temperature should be carried out.

### 6.3 Calculate the flue gas temperature

As shown in Fig. 6.2, in the preheating and firing zone, tunnel kiln can be seems as a heat exchanger. According to the temperature profile shown in Fig. 6.2, the temperature \( T_A \) can be calculated according to the solution for heat exchanger

\[ T_A = T_\infty + (T_{\text{ad}} - T_\infty) \cdot \exp\left[\left(1 - \Omega\right) \cdot St\right] \] \hspace{1cm} (6-18)

and \( T_\infty \) can be calculated as

\[ T_\infty = \frac{T_{\text{ad}} \cdot \exp\left[\left(1 - \Omega\right) \cdot St\right]}{\exp\left[\left(1 - \Omega\right) \cdot St\right] - \Omega} \] \hspace{1cm} (6-19)

where \( St \) is Stanton number, it can be expressed

\[ St = \frac{k \cdot A}{M_S \cdot c_S} \] \hspace{1cm} (6-20)

\( k \) is the overall heat transfer coefficient, and \( A \) is the heat transfer area.

The heat capacity ration \( \Omega \) is equal to

\[ \Omega = \frac{\dot{M}_S \cdot c_S}{\dot{M}_G \cdot c_{pg}} \] \hspace{1cm} (6-21)

The mass balance Eq. (6-11) results the heat capacity ration \( \Omega \)

\[ \Omega = \frac{(1 + \lambda \cdot L) \cdot \dot{M}_i \cdot c_{pg}}{\dot{M}_S \cdot c_S} \] \hspace{1cm} (6-22)

If the equation to express the specific energy requirement
\[
E = \frac{\dot{M}_f \cdot h_u}{M_s}
\]

(6-23)

is put into the Eq. (6-22), the following equation can be obtain

\[
\Omega^{-1} = \frac{(1 + \lambda \cdot L) \cdot \dot{M}_f \cdot c_{pG} \cdot E}{\dot{M}_f \cdot h_u} = \frac{(1 + \lambda \cdot L) \cdot c_{pG} \cdot E}{h_u}
\]

(6-24)

For the calculation of the adiabatic temperature \(T_{ad}\), the energy balance for the combustion chamber is applied:

\[
\dot{M}_f \cdot h_u + \dot{M}_L \cdot c_{pL} \cdot T_L = \dot{M}_o \cdot c_{pG} \cdot T_{ad}
\]

(6-25)

with mass balance Eq. (6-10) and (6-11),

\[
T_{ad} = \frac{\dot{h}_u}{c_{pG} \cdot (1 + \lambda \cdot L)} + T_L
\]

(6-26)

Now with the five Eq. (6-12), (6-18), (6-19), (6-24) and (6-26), the five variables \(E\), \(T_A\), \(T_c\), \(\Omega\) and \(T_{ad}\) are solvable.

Fig. 6.3 shows the influence of Stanton number and air access number on specific requirement. It can be seen, that the higher the heat transfer area \(A\), the higher the Stanton number \(St\), the lower the energy requirement \(E\). However, the higher the heat transfer area, the higher the kiln size, and therefore, the higher the investment cost.

![Figure 6.3: Energy requirement depending on Stanton number](image)

Fig. 6.3 also tells that the higher the air access number, the higher the energy requirement. Therefore, the air access number should be adjusted as lower, depending on the better mixture of air and fuel.
6.4 Overall heat transfer coefficient $k$

The simplified process shown in Figure 6.2 considers the temperature of the solid is homogenous. But the real process shown in Figure 6.1 shows the temperature different between the surface and core of the solid. Therefore, the heat conduction inside of the solid should be considered. In order to compensate the heat conduction inside the solid, overall heat transfer coefficient $k$ is used.

![Figure 6.4: Temperature profile inside the brick](image)

The heat flux from the gas to the solid can be calculated with the convective heat transfer coefficient and the temperature difference between the gas environment temperature $T_G$ and solid surface temperature $T_{sw}$

$$\dot{q} = \alpha \cdot (T_G - T_{sw})$$  \hspace{1cm} (6-27)

$\alpha$ is the heat transfer coefficient, it can be obtained from Nu function.

$$\alpha = \frac{Nu \cdot \lambda_g}{d_h}$$  \hspace{1cm} (6-28)

For the tunnel kiln calculation, solid mean temperature $T_s$ is applied. Therefore overall heat transfer coefficient $k$ is used to express the heat conduction inside the solid.

$$\dot{q} = k \cdot (T_G - T_s)$$  \hspace{1cm} (6-29)

$k$ is the overall heat transfer coefficient or effective heat transfer coefficient, it contains the terms of heat transfer and the heat conduction inside the brick, and can be calculated as:

$$\frac{1}{k} = \frac{1}{\alpha} + \frac{s/2}{\chi \cdot \lambda_s}$$  \hspace{1cm} (6-30)

where $\alpha$ is the convective heat transfer coefficient, and $\chi$ is the shape dependent transient factor. According to the shape, following values are applied.
\[
\chi = \begin{cases}
3 & \text{plate} \\
4 & \text{cylinder} \\
5 & \text{sphere}
\end{cases}
\]
7. Development counter-travelling tunnel kiln

7.1 Introduction

As discussed above, tunnel kilns consist of a series of one after another connected counter-current heat exchangers and therefore require principally relatively low energy consumption due to the obtained heat recovery. However, comparing to the other production process, the tunnel kiln process has relatively low energy efficiency. There is a big potential to improve the tunnel kiln process.

The main disadvantage of tunnel kiln is that only one of the two with each other exchanged mass flows becomes useful, while the other - that is to say air or kiln gas - only produce a ballast mass. Therefore, the air flow in tunnel kiln plays the roles of both counter-current energy carrier and heat transfer medium.

The solution to this problem is that the recuperation is not between the product flow and air or flue gas, but between the two counter-travelling product flows, the function of the air and the flue gas in the tunnel kiln is therefore mainly to serve as a heat transfer medium for the two counter travelling solid mass flows, between which there are heat transfers for each other.

The Schematic view of counter-travelling kiln is shown in Fig. 7.1. It consists of two parallel for each other counter travelling product mass in the reverse direction. The firing zone of the two channels locate in the middle of the kiln at the same position, and the cooling zone of one channel is located beside the preheating zone of the other channel. This makes the hot fired products just coming out from the firing zone of one channel directly transfer its heat to the unfired green products of the other channel, and thus provides preheating up to the firing zone, and cooling in the cooling zone.

![Figure 7.1 Schematic Diagram of Counter travelling Tunnel Kiln](image-url)
The cross section of the counter-travelling tunnel kiln is shown in Fig. 7.2. The two for each other counter travelling product mass flow form a solid-solid recuperator, which in the cross section of the both product flows in the kiln channel, recirculation air between the both sides takes the function of intermediated-carrier. It saves heat by absorption of the hot side and then releases the heat to the cold side. In order to keep the stable gas recirculation in the cross section, ventilators are installed on the top of the kiln in the preheating and cooling zone. The ventilator used here is the ventilators, which can work under high temperature up to 900°C. Under the performance of the ventilator, stable gas recirculation in the cross section can be ensured.

![Figure 7.2 Schematic cross section of the counter travelling tunnel kiln](image)

### 7.2 Model

The total model of the kiln is simplified with the description of Fig. 7.3. The recirculation gas in hot side of the kiln flows from the bottom with the temperature $\vartheta_{g,bot}$ into the brick gaps. After the gas flows through the gaps, it is warmed up to temperature $\vartheta_{g,top}$ and flows out of the gaps. Then, the gas flows through the ventilators to the other side of the kiln, where the gas temperature remains approximately constant. During flow through the cold brick gaps, the gas temperature is cooled down to $\vartheta_{g,bot}$ again.
The distance of the brick gap is $s$, the brick width is $b$ and the bricks height is $H$. The width of each kiln part is $B/2$. The length element of the kiln is $\Delta L$. The used coordinate designations are indicated in the figure.

Following are the simplifications made for the model:

- The process is assumed as a steady process, the kiln cars are pushed into the kiln continuously, but not step by step. Thus the temperatures at any cross section remain temporally constant.
- No temperature variation along the brick height ($Y$-direction), and $\Theta_1$ and $\Theta_2$ are temperature on each side.
- The material properties of the gas are calculated at the mean temperature of top and bottom of the gap, and are assumed constant.

Energy balance can be written for each kiln element along the kiln length: In each kiln segment element, the enthalpy change of the gas through the brick pile gap is equal to the enthalpy change of bricks along the kiln length.

$$\dot{H}_g = \dot{H}_b.$$  \hfill (7-1)

The enthalpy change of the gas through brick pile gap is

$$\dot{H}_g = \dot{M}_g \cdot c_{pg} \cdot (\Theta_{g,1} - \Theta_{g,b})$$  \hfill (7-2)
while the enthalpy change of brick along the kiln length is

\[ H_s = \dot{M}_s \cdot c_s \frac{d\theta_s}{dL}, \quad (7-3) \]

where \( \dot{M}_s \) is the mass flow of bricks, which is equal to the throughput of the kiln, \( \theta_s \) is the mean temperature of the bricks, \( c_{p,g} \) and \( c_s \) are mean specific heat capacities of gas and brick respectively. The enthalpy change of the gas is equal to the heat transferred to the brick.

Since the temperature of the brick is assumed to be constant at each position, the temperature change of the gas can be calculated with the Newton's capacity model. In each gap in the hot side:

\[ \frac{\theta_{g,\text{top}} - \theta_1}{\theta_{g,\text{bottom}} - \theta_1} = \exp\left( -\frac{A \cdot \alpha_{\text{eff.}}}{\dot{M}_g \cdot c_{p,g}} \right) \quad (7-4) \]

while in the cold side

\[ \frac{\theta_{g,\text{bottom}} - \theta_2}{\theta_{g,\text{top}} - \theta_2} = \exp\left( -\frac{A \cdot \alpha_{\text{eff.}}}{\dot{M}_g \cdot c_{p,g}} \right) \quad (7-5) \]

where

\[ A = 2 \cdot H \cdot \Delta L \quad (7-6) \]

is the heat transfer surface in each gap and \( \alpha_{\text{eff.}} \) is the effective heat transfer coefficient. Therefore the temperature difference of the gas is according to the above equations is

\[ \Delta \theta_g = \frac{1 - \exp\left( -\frac{2 \cdot H \cdot \Delta L \cdot \alpha_{\text{eff.}}}{\dot{M}_g \cdot c_{p,g}} \right)}{1 + \exp\left( -\frac{2 \cdot H \cdot \Delta L \cdot \alpha_{\text{eff.}}}{\dot{M}_g \cdot c_{p,g}} \right)} (\theta_1 - \theta_2) \quad (7-7) \]

For this calculation, the mass flow of the gas and the effective heat transfer coefficient are needed, which should be determined at first. The temperature of the bricks is not constant over the cross section, but because of the unsteady cooling and heating, the temperature appears an approximately parabolic profile as illustrated in Fig. 7.4. Thus, the effective heat transfer coefficient includes the convective heat transfer on the surface and heat conduction inside the solid. It is defined as

\[ \alpha_{\text{eff.}} = \frac{1}{\frac{1}{\alpha_{\text{conv.}}} + \frac{\lambda_s}{\chi \cdot \lambda_s}} \quad (7-8) \]
Here $\lambda_s$ is the heat conductivity of the brick and $\chi$ is the transient factor and it dependents on the geometry. For the approximately linear temperature changes of the brick, the values 3, 4, 5 can be taken for the plate, the cylinder and the sphere respectively. Here the value 3 is used for brick pile as it can be approximated as in plate form.

![Figure 7.4 Principle temperature profile in cross section of brick](image)

The convective heat transfer coefficient can be obtained from Nusselt's Number $\text{Nu}$

$$a_{\text{conv.}} = \frac{\text{Nu} \cdot \lambda_g}{d_h} \quad (7-9)$$

where $\lambda_g$ is the mean heat conductivity of the gas and $d_h$ is the hydraulic diameter. The flow between the brick piles can be seen as a rectangular gap. Because the length is relatively much higher than the thickness, the approximation can be used as

$$d_h = 2 \cdot s \quad (7-10)$$

For the rectangular gap, the Nusselt functions are

$$\text{Nu} = \sqrt{\text{Nu}_{\text{lamm}}^2 + \text{Nu}_{\text{turb}}^2} \quad (7-11)$$

$$\text{Nu}_{\text{lamm}} = \sqrt{3.66^3 + 1.61^3 \cdot \text{Re} \cdot \text{Pr} \cdot \frac{d_h}{H}} \quad (7-12)$$

$$\text{Nu}_{\text{turb}} = 0.0214 \cdot (\text{Re}^{0.8} - 100) \cdot \text{Pr}^{0.4} \cdot \left[1 + \left(\frac{d_h}{H}\right)^{0.67}\right] \quad (7-13)$$

The Reynolds number is defined as

$$\text{Re} = \frac{w_g \cdot d_h}{v_g} \quad (7-14)$$

where $v_g$ is the viscosity of the gas and $w_g$ is the gas velocity inside the gap.
The gas velocity is dependent on the power of the ventilators $P_{el}$ and the pressure drop. They are connected as:

$$P_{el} \cdot \eta_{ls} = \dot{V}_g \cdot \Delta p_v$$  \hspace{1cm} (7-15)

Here, $\eta_{ls}$ is the efficiency of the ventilators. For the high temperature ventilators used here, the efficiency is usually $0.7$.

The total gas volume flow depends on the number of brick piles $n$ in the cross section and the length of the kiln $\Delta L$, which is the length of the kiln segment:

$$\dot{V}_g = (n + 1) \cdot s \cdot \Delta L \cdot w_g$$  \hspace{1cm} (7-16)

![Figure 7.5: Schematic diagram of the pressure drops in cross section](image)

The gas recirculation pressure drops in the cross section is shown in the Fig. 7.5. After coming out of the ventilator, the gas must flow into the gaps, then, after the wall friction, it flows out of the gaps again, undergoing $90^\circ$ elbow turn over, it flows to the other side of the kiln, there, the gas flows into the gap again, experiences the wall friction, flows out of the gaps again and then must go through the tube to the ventilator. The pressure drop for the flow from one kiln side to the other kiln side can be neglected, because here the cross section area is very big and therefore the gas flow velocity is very small. The pressure drops for the total recirculation are therefore as following

$$\Delta P_v = \frac{1}{2} \cdot \rho_g \cdot w_g^2 \left[ \left( \xi_1 + \xi_2 + \lambda \cdot \frac{H}{d_h} + \xi_3 + \xi_4 \right)_{\text{left}} + \left( \xi_1 + \xi_2 + \lambda \cdot \frac{H}{d_h} + \xi_3 + \xi_4 \right)_{\text{right}} + \xi_5 \right]$$  \hspace{1cm} (7-17)

The pressure drop coefficients of the gas recirculation are concluded in Table 2.1. The values of both fluid turn over and ventilator system were calculated by using commercial CFD package FLUENT 6.3, which will be discussed in another separate chapter.

**Table 7.1: Pressure drop coefficient of gas recirculation**

<table>
<thead>
<tr>
<th></th>
<th>left</th>
<th>right</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_1$</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>$\xi_2$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
With these equations, the gas velocity inside of the brick pile can be expressed as

$$w_g = \frac{\mathbf{P}_e \cdot \eta_s}{(n+1) \cdot \rho_g \cdot s \cdot \Delta L \left( \xi_1 + \xi_2 + \lambda \cdot \frac{H}{d_h} + \xi_3 + \xi_4 + \frac{\xi s}{2} \right)}^{1/3}.$$  \hfill (2-18)

The material properties for the gas are determined by the mean temperature

$$\bar{\theta} = \frac{\theta_{g,\text{top}} + \theta_{g,\text{bottom}}}{2}.$$  \hfill (7-19)

By coupling Eq. (7-4) and (7-5) together, the mean temperature can also be expressed as

$$\bar{\theta} = \frac{\theta_1 + \theta_2}{2}.$$  \hfill (7-20)

The temperature dependent material properties can be approximated by the following equations with an error smaller than \(\pm 3\%\)

$$\frac{\rho_g}{\rho_{0,g}} = \left( \frac{T}{T_0} \right)^{n_c}, \quad \frac{c_{p,g}}{c_{p,0,g}} = \left( \frac{T}{T_0} \right)^{n_v}, \quad \frac{v_g}{v_{0,g}} = \left( \frac{T}{T_0} \right)^{n_s+1}, \quad \frac{\lambda_g}{\lambda_{0,g}} = \left( \frac{T}{T_0} \right)^{n_\lambda}.$$  \hfill (7-21)

The exponent indexes for air are concluded in Table 7.2. These values can also be used for combustion gas.

| \(\rho_{0,g}\) | \(c_{p,0,g}\) | \(n_c\) | \(v_{0,g}\) | \(n_v\) | \(\lambda_{0,g}\) | \(n_\lambda\) |
| [kg/m³] | [J/kg·K] | [-] | [m²/s] | [-] | [W/m·K] | [-] |
| 1.29 | 1000 | 0.10 | 13.5×10⁻⁶ | 0.67 | 0.025 | 0.76 |

With the above explained equation series, the power of the ventilators can be calculated as functions of geometric parameters and process parameters.

$$P_e = f(b,n,s,H,\Delta L,\Delta \vartheta_s,\dot{M}_s)$$

The geometric parameters are: brick pile width \(b\), brick height \(H\), number of the brick piles \(n\) in each side and gap thickness \(s\).

And the process parameters are: kiln length \(\Delta L\) for one ventilator, temperature difference between both kiln sides \(\Delta \vartheta_s\) and the brick throughput \(\dot{M}_s\).
7.3 Results and discussion

At first, the ventilator power per length is investigated, because this can determine heat transfer and furthermore the operation mechanism of the kiln. In Fig. 7.6 the dependence of ventilator power on the brick pile gap thickness is shown, with the gas temperature as parameter. The curves are principally the same shape. It is indicated in the range of 1 to 2 cm, there is a minimum value, where is outlined by a dash line. The minimum value is based on the connection of volume flow and pressure drop. When the gap thickness is decreased from very big to small values, the ventilator power decreases, this is the effect of the decrease of the volume flow; while if the gap further increase smaller than the optimal value, the ventilator power increases again, this is due to the effect of increase of the pressure drop of the gas recirculation. The higher the gas temperature, the higher the gas viscosity and the lower the gas density, and therefore, the lower enthalpy flow is transported. This must be compensated by higher ventilator power.

![Figure 7.6: Ventilator power per length at different gap thickness and gas temperatures](image)

As a parameter, the bricks temperature difference between the both kiln sides $\Delta \theta_s$ is investigated. In Fig. 7.7 the ventilator power dependence on the gap thickness is shown again, and with the bricks temperature difference between the both sides $\Delta \theta_s$ as parameter. The higher the temperature difference $\Delta \theta_s$ is, the lower the heat transfer volume flow required, and therefore the lower ventilator power is.

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However, the higher the temperature difference $\Delta \vartheta_s$, the higher temperature the brick move out of the kiln. Therefore, the driving out temperature is also high. This contains not only the enthalpy of the brick, but also kiln car. According to experience, the driving loss of the kiln car is $1/3$ of the brick. In Fig. 7.8 the specific driving out loss of brick including the driving out loss of the kiln car and flue gas loss are shown. It increases linearly with the increase of the temperature difference.

Fig. 7.9 shows the total specific energy requirement of the kiln dependence on the bricks temperature difference of both sides $\Delta \vartheta_s$, which is the sum of the fuel energy and the primary energy of the ventilator power. It is shown that there is a minimum value of total energy when the bricks temperature difference of both sides $\Delta \vartheta_s$ in the range of 160 °C to 190 °C. The course of the curve within this range is very flat, so the exact adjustment of the temperature difference is not so crucial, this makes the
operation of the kiln is easier. Compared to the fossil fuel energy, the ventilator power is relatively small.

![Graph showing energy consumption](image)

**Figure 7.9:** Sum of the fossil energy and primary ventilator power

In the Table 7.3 the energy consumptions of traditional tunnel kiln and new tunnel kiln process are compared. The total energy consumption is divided into different parts. The mean specific energy consumption of traditional process for the full brick is 2.3 MJ/kg brick. This is divided to 1.05 MJ/kg for the drying process and 1.25 MJ/kg for the kiln process. The drying energy is consists of around 60% for the water condensation enthalpy (0.62 MJ/kg) and 40% for the flue gas enthalpy of drying (0.43 MJ/kg).

In the new kiln process, the mean driving out temperatures are 215°C to 195°C, which is the temperature difference of both sides $\Delta \theta_s$ plus 25°C of the driving-in bricks. These temperatures are below those of traditional kilns. This can be explained by the fact that the new concept has better heat transfer under the works of ventilators. Therefore, the driving out losses of the brick and kiln cars are lower. The heat losses from the kiln wall are kept as constant for all kilns. The most significant difference of the old and new kiln process is the flue gas losses. This in the new kiln process is just 0.1 KJ/kg, only around 11% of the traditional process. For the new kiln, however, the energy for the ventilator has to be included. Here, the electrical energy is converted to the primary energy by a power station efficiency of 35%.

For the conclusion, it is evident that, for the kiln process itself, 62% and 65% energy can be saved. For the total process, 43% to 44% energy can be saved.
### Table 7.3: Comparison of energy saving of the both kiln processes

<table>
<thead>
<tr>
<th>Item</th>
<th>Traditional tunnel kiln</th>
<th>Counter travelling tunnel kiln</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s=60mm</td>
<td>s=20mm</td>
</tr>
<tr>
<td>Dryer 25% water vaporization</td>
<td>0.62</td>
<td>1.05</td>
</tr>
<tr>
<td>Flue gas, enthalpy change of bricks</td>
<td>0.43</td>
<td>0.22</td>
</tr>
<tr>
<td>Driving loss from bricks</td>
<td>0.22</td>
<td>1.25</td>
</tr>
<tr>
<td>Driving loss from kiln car</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Ca. 33% of bricks</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Insulation loss</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td>Flue gas loss</td>
<td>0.85</td>
<td>0.10</td>
</tr>
<tr>
<td>Electrical energy for blowers (primary)</td>
<td>0</td>
<td>0.034</td>
</tr>
<tr>
<td>Whole process</td>
<td>2.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

The energy save can be obviously seen. However, on the contrary, the saved energy faces the problem of high investment costs. High investment costs are specially consist of rebuilding the traditional kilns into the new process. Not so high investment costs are expected, if a complete new kiln is built. Such investment costs are not able to be estimated, and therefore is not contains here.

### 8. Other kilns for ceramics manufacturing

#### 8.1 Intermittent (periodic) kilns

These include shuttle and hood-type kilns, based on single chambers, which are charged with pre-dried ceramic products (in a hood-type kiln, the hood equipped with the heating unit is placed on the bottom by a hoisting unit; in shuttle kilns, the ware to be fired is brought to the hearth area in a shuttle car), sealed, and then subjected to a defined firing cycle. Gas burners are usually employed and good control of temperature and kiln atmosphere (oxidising or reducing) can be achieved.

Electricity can also be used to heat intermittent kilns, for instance in the manufacture of technical ceramics. Special kiln types for technical ceramics are, e.g. HIP (hot isostatic pressing), high temperature kilns, and kilns with a protective atmosphere.

Intermittent kilns are mainly used for smaller scale manufacture of specialised products, such as special shaped bricks and pipe fittings, roof tile fittings, refractory products, etc. They offer flexibility when the ceramic body composition is altered frequently, and these advantages outweigh their somewhat lower energy efficiency. The following figures show the cross-section of a shuttle kiln.
8.1.1 Shuttle kiln

These kilns are periodic kilns like "Chamber Kiln", but kiln car(s) are used for convenience of loading / unloading and storage of products. Shuttle kiln for firing sanitary ware, metal, table ware, roof tiles, insulators, advanced ceramic.
8.2 Continuous kilns

8.2.1 Hoffmann kiln

The Hoffmann Kiln is a series of batch process kilns. Hoffmann Kilns are the most common kiln used in production of bricks and some other ceramic products. A Hoffmann kiln consists of a main fire passage surrounded on each side by several small rooms. Each room contains a pallet of bricks. In the main fire passage there is a "fire wagon", that holds a fire that burns continuously. Each room is fired for a specific time, until the bricks are vitrified properly, and thereafter the fire wagon is rolled to the next room to be fired.

Each room is connected to the next room by a passageway carrying hot gases from the fire. In this way, the hottest gases are directed into the room that is currently being fired. Then the gases pass into the adjacent room that is scheduled to be fired next. There the gases preheat the brick. As the gases pass through the kiln circuit, they gradually cool as they transfer heat to the brick as it is preheated and dried. This is essentially a counter-current heat exchanger, which makes for a very efficient use of heat and fuel. This efficiency is a principal advantage of the Hoffmann kiln, and is one of the reasons for its original development and continued use throughout history.

In addition to the inner opening to the fire passage, each room also has an outside door, through which recently-fired brick is removed, and replaced with wet brick to be dried and then fired in the next firing cycle.

The Hoffmann Kiln is used in non-developed countries, and in current and former developing countries. In a classic Hoffmann kiln, the fire may burn continuously for years, even decades. In Iran, there are kilns that are still active and have been working continuously for 35 years.

Any fuel may be used in a Hoffmann kilns, including gasoline, natural gas, heavy petroleum and wood fuel.

The dimensions of a typical Hoffmann kiln are completely variable, but in average about 5m (height) x 15m (width) x 150m (length).

Patented by German Friedrich Hoffman for brickmaking in 1858, it was later used for lime-burning, and was known as the "Hoffman Continuous Kiln".

The original Hoffmann Kiln

The first Hoffmann kilns were in the form of a great circular ring chamber, with massive walls and a large chimney at the centre, to which underground radial flues converged from the inside walls of each of the twelve chambers. The chambers were barrel arched (like a railway tunnel), and in the roof arches there were several small feed holes through which fine coal could be fed into spaces made among the bricks to be fired. Around the outer wall or the kiln were the twelve openings for loading and unloading the individual firing chambers. These chambers were seperated from each
other by very large metal dampers, that could be raised and lowered as the fire moved around the kiln from chamber to chamber.

Once the kiln is lit it is allowed to go out, and the sequence of operation is continuous. With the kiln in full operation two chambers will be open, and the other ten sealed up at the door and by the interconnecting steel dampers. If the chambers are numbered from 1 to 12, then bricks are being unloaded from 2 and loaded in 1. The damper is closed between 1 and 12, but open between all other chambers. Air is drawn through the open door of 2 and through the bricks in 3, 4, 5, and 6, cooling them down and at the same time being heated itself.

The temperatures of the chambers increase from 3 to 6, with the temperature at 6 being close to the firing temperature.

Chamber 7 is being fired, with fuel being fed at intervals through the roof, which is immediately ignited by the hot air from 6. The products of combustion pass on to 8, 9, 10, and 11 drying and pre-firing the bricks in these chambers. In 8, the bricks are at the pre-firing stage, and in 11 they are going through the water smoking stage. From 11 the combustion gases pass through the flue and up the central chimney. All the other 11 flues from the other chambers are closed off with dampers. At regular intervals, the firing zone is moved forward and the corresponding changes made to the dampers between the chambers and into the chimney. The chambers being loaded and unloaded move forward in sequence, and this way heat is extracted from the cooling bricks and also from the hot combustion gases.
The original round Hoffman kiln is no longer in use, having been replaced by the more modern version, which takes the form of two parallel tunnels built side by side, connected by curved tunnels at either end. With such an arrangement, the chimney is built outside the kiln structure and may be connected to more than one kiln. Sixteen chambers are about the minimum for effective working; twenty-two chambers are preferable. The original Hoffmann was superseded, because it had such a large heat absorbing mass, and the tapering firing chambers were small and unnecessary complicated to load, while the very large damper between chambers was cumbersome and awkward to operate. This damper was replaced by the pasting of a paper or fabric screen between the sections of the firing tunnel as it is loaded. The screen seals the tunnel at this point and prevents cold air being drawn the wrong way round the kiln to the firing zone. The screen is destroyed by the approaching firing zone, at just the right time, as it moves around the kiln.

There are now many different designs of continuous kiln, based on the moving firing zone perfected in the Hoffmann kiln, but the basic principal of the moving firing zone, coupled with continuous loading and unloading, remains the same.
The path of fire travel in the original Hoffmann was circular, later distorted into an ellipse, the arch of the tunnel being supported on the side walls. In order to increase output, continuous kilns with longer circuits through which the firing zone travels more rapidly are built. Two firing zones running simultaneously are possible on the larger kilns. To save space, the firing circuit is bent into a Zig Zag form. Other designs, in which the circuits are built in the form of a \( T \), \( Y \) or \( X \), with the chimney in the centre, are also used. In principal, they do not differ from the Hoffmann Kiln, but with a high rate of fire travel, assisted by a strong fan draught system, they are still popular in some countries.

\[\text{Figure 8.3: Modern hoffmann kiln}\]

### 8.2.2 Roller hearth kiln

The roller hearth kiln is a prefabricated continuous kiln of which hearth is formed of motor driven roller way(s). The goods to be fired are therefore automatically conveyed from the kiln entrance to the exit on the roller way. (The goods shall be loaded on refractory plates or batts in case they are not suitable to be loaded on the rollers directly.) Because no other things than the goods and refractory plates pass through the kiln, this type of kiln’s thermal efficiency is superior to other types. Also considerably short firing cycle is another feature of this type of kiln.

The roller hearth kiln has mostly single layer of hearth and consists of 2.1 meter long prefabricated modules in principle so that any large sized one can be loaded in sea freight containers and therefore packing, shipping & transport costs are minimized. Thanks to prefabrication system, installation of this type of kiln at the spot is so fast as 4-5 weeks.
roller kilns are now almost universally used for wall and floor tile production, and firing schedules have been reduced to less than 40 minutes. Tiles travel over driven rollers, and the heat required for firing is provided by natural gas-air burners located at the sides of the kiln. The main heat transmission mechanisms are convection and radiation, and as the kilns are non-muffled, the heat transmission coefficients are raised, reducing the firing cycle and energy consumption. Roller hearth kilns are also sometimes used for the production of clay roof tiles, vitrified clay pipes, sanitaryware and tableware. The following figure shows the cross-section of a roller hearth kiln.

![Figure 8.4: View of roller kiln](image)

The heat transfer mechanisms will be explained through the following figure, which shows the transport rolls and goods.
In the contact area located between $\varphi_1$ and $\varphi_2$, the heat will transfer from the roll to the goods. In other area, the roll gets the heat through radiation from the kiln gas. This heat will be stored into the roll. This will make the temperature increase from the $\vartheta_2$ to $\vartheta_1$ during the rotation way from the $\varphi_2$ to $\varphi_1$. In the contact area, the heat from the roll will give again to the goods.

Figure 8.5: Principle of heat transfer mechanisms of roller kiln