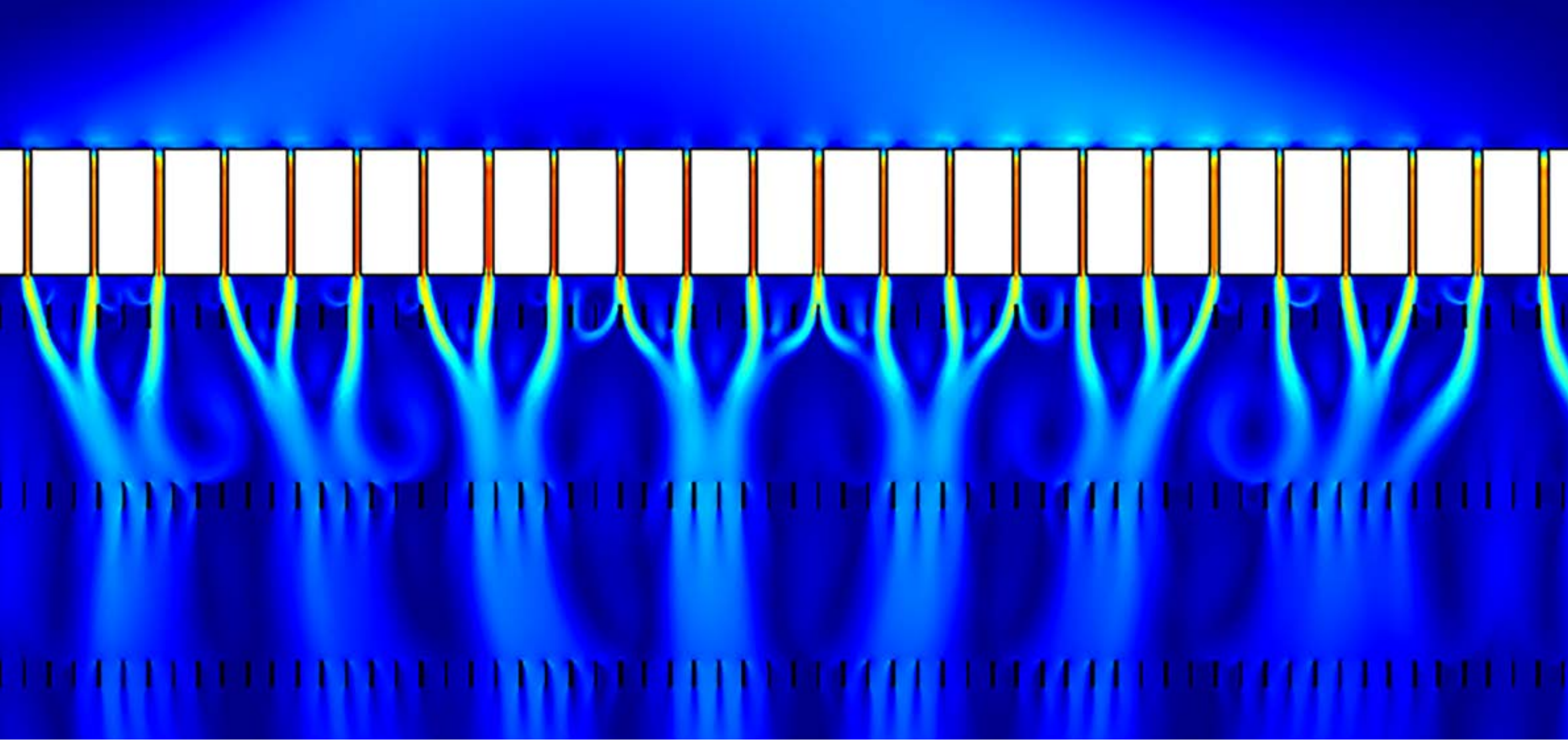
Fraunhofer IGB

Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB

Superheated Steam Processing at Atmospheric Pressure

Energy-efficient technology for drying, roasting and torrefaction



The challenge of energy efficiency

Drying is an important and frequently used process in various branches of industry. It is often an essential process step in the production, treatment and processing of solid materials. Conventional drying processes with air consume a large part of the energy required in the overall production process chain. Thus, considering the criticality of energy supply, industry is called to intensify efforts to reduce the energy required for drying and consequently increase the industrial energy efficiency.

On one hand, the choice of the most energy-efficient technology and its correct implementation play a major role. The recovery of previously unused energy e.g. residual or exhaust heat, on the other hand, has become of particular focus of the industry. Only in this way energy costs and CO_2 emissions caused by the production of energy can be significantly reduced.

To meet this challenge, the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB is working on the further development of an innovative drying process with superheated steam at atmospheric pressure. This technology permits significant energy savings, while at the same time maintaining high product quality. Furthermore, the use of this process does not only increase the efficiency of energy utilization, but also of material usage by enabling the capture of valuable volatiles compounds that are carried out together with the steam.

Competencies and collaboration

Fraunhofer IGB possesses proven expertise in the research, development and process application of drying processes for industrial customers and has at its disposal both stationary and mobile laboratory equipment and pilot plants. This includes equipment for the analytical evaluation of processes used and software tools for modeling and designing prototypes.

Together with industrial partners, Fraunhofer IGB supports clients from the conception phase by way of process design and assembly to the full in-house operation of the customized solution.

Industrial drying

The current situation

Drying generally represents an essential process step in the production, treatment and processing of solid materials. For example, drying processes are used, for stabilizing the form of granulates, pellets or powders. Other desirable properties of products such as shelf life, weight reduction or microbiological stability are also achieved through drying.

Drying processes typically work with hot or warm air. In many cases, a large part of the energy required in the whole processing chain is used for drying. Furthermore, these drying processes often require a long residence time and therefore considerable space. According to various studies, approx. 20–25 percent of the total industrial energy consumption is used for drying[1,2].

State of the art

Drying is considered a thermal dehumidification process in which the moisture is removed from the moist material by evaporation, transforming liquid water into steam. The higher the moisture content of the input material, the more energy is required for drying.

The thermal drying process consists of three essential subprocesses:

1. transferring the heat from the drying medium to the moist material,
2. the phase transition of the moisture into steam, and
3. transport of the resulting steam to the atmosphere of the drying medium by means of diffusion.

In convective drying processes, the required thermal energy is supplied through the stream of drying gas. Conventionally, ambient air is heated to the desired temperature using fossil fuels (mainly natural gas) and employed as drying gas. In some cases, if organic solvents are to be removed or ignitable solids are to be dried, a nitrogen-based inert gas circulation method has to be applied. The cost of the drying process depends directly on the volume of the drying medium and the drying time required. These determine the size of the dryer and the peripheral equipment.

Technical limitations of conventional hot-air drying

With the currently used air-based drying processes, environmentally harmful emissions are released with the exhaust gas. In addition to CO_2, the exhausted gas may contain volatile bases, ammonia, fatty acids, and sulfur compounds, which are also often responsible for odor nuisances. In order to comply with the emission regulations, a costly downstream gas treatment unit is required additionally. Furthermore, together with the exhausted gas, thermal energy and valuable volatile substances, which could have been valorized for other applications, are also lost.

A further problem in air-based drying processes is the formation of an explosive mixture of oxygen, whirled up dust and/or solvent. To minimize the risk of explosion, the law requires costly measures in accordance with ATEX Guidelines[3], which often result in complex and cost-intensive construction and operation measures of the drying plant, for example pressure-surge protected systems or inert gas operation.

1 Strumillo, C.; Jones, P.; Zylla, R. (1995) Energy Aspects in Drying, Handbook of Industrial Drying, 2nd Ed.; Mujumdar, A. S., Ed.; Marcel Dekker: N. Y.

2 https://energieforschung.at/projekt/effiziente-trocknung-mit-kompressionswaermepumpen/

3 European Commission (2011): ATEX guidelines, ec.europa.eu/enterprise/sectors/mechanical/files/atex/guide/atexguidelines-may2011_en.pdf

New process with superheated steam

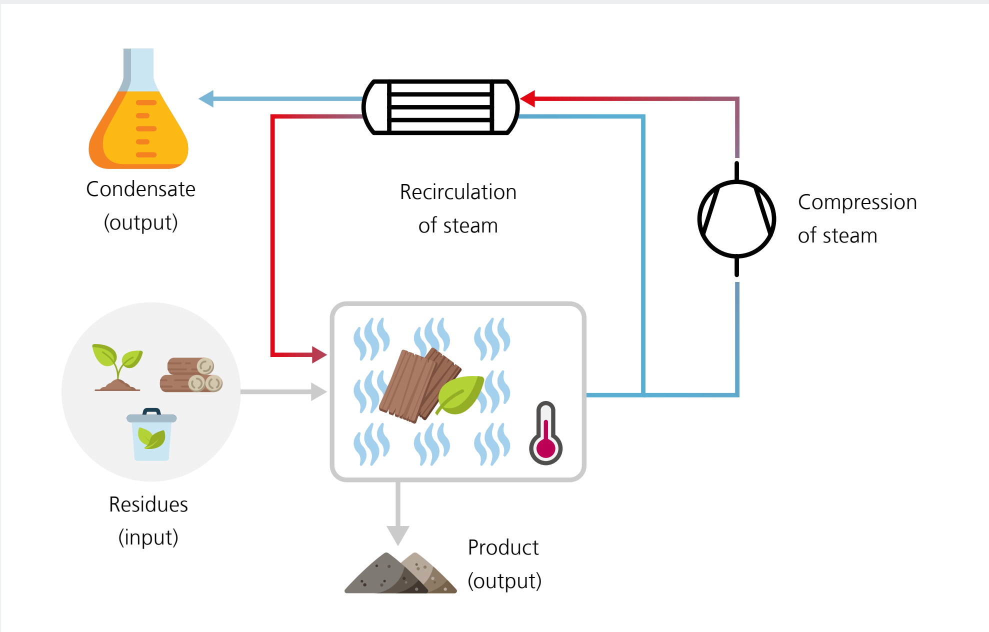
Energy consumption is an important economic factor in industrial mass production. Savings can be achieved by means of energy recovery, optimized process engineering or multiple use of the energy flows. For these purposes, superheated steam (SHS) drying can play an important role.

Reduced specific energy consumption

The thermodynamic properties of superheated steam have some advantages over hot air. The specific heat capacity, one of the factors responsible for heat transfer, is twice that of hot air (*heat transfer compared under the same conditions). Another thermodynamic property that can be compared is the viscosity of the gas, which is three times lower for superheated steam than for hot air. The viscosity of the gas is crucial for the drying process, as it determines the rate of gas diffusion in the capillary of the material; the lower the viscosity, the faster the gas diffusion (Stoke-Einstein equation). These advantages contribute to a 30 percent reduction in specific energy consumption under optimized drying conditions, depending on the capillary structure of the material.

The specific energy consumption of SHS drying processes can be further reduced by applying recovery of energy. Three options are possible:

- Condensation of excess steam at atmospheric pressure: The energy of evaporation can be recovered entirely at a lower temperature level (90 – 95 °C).
- Coupling with a closed-loop heat pump: A high-temperature heat pump is used to increase the temperature level of the condensation heat at 90 °C to about 140 – 160 °C in order to supply the drying process with energy.
- Coupling with an open-loop heat pump (Mechanical Vapor Compression): The excess steam is not condensed but compressed to a higher-pressure level. This high-pressure steam is then condensed to supply the drying system with high temperature heat (140 – 160 °C) (see picture below)

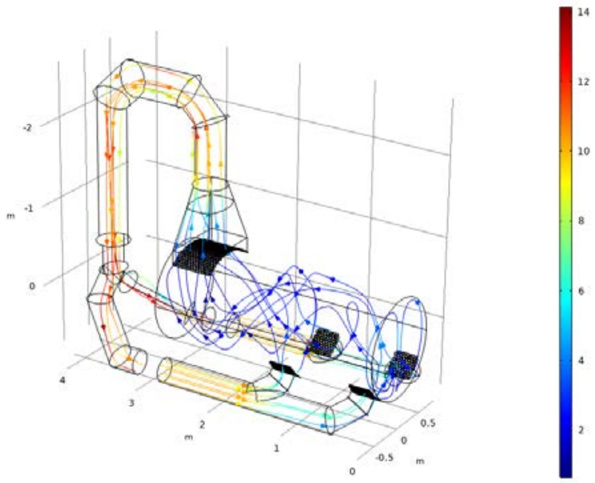


Energy optimization of the drying through steam compression

There is no risk of explosion during the torrefaction of wood in a steam atmosphere.

Further advantages

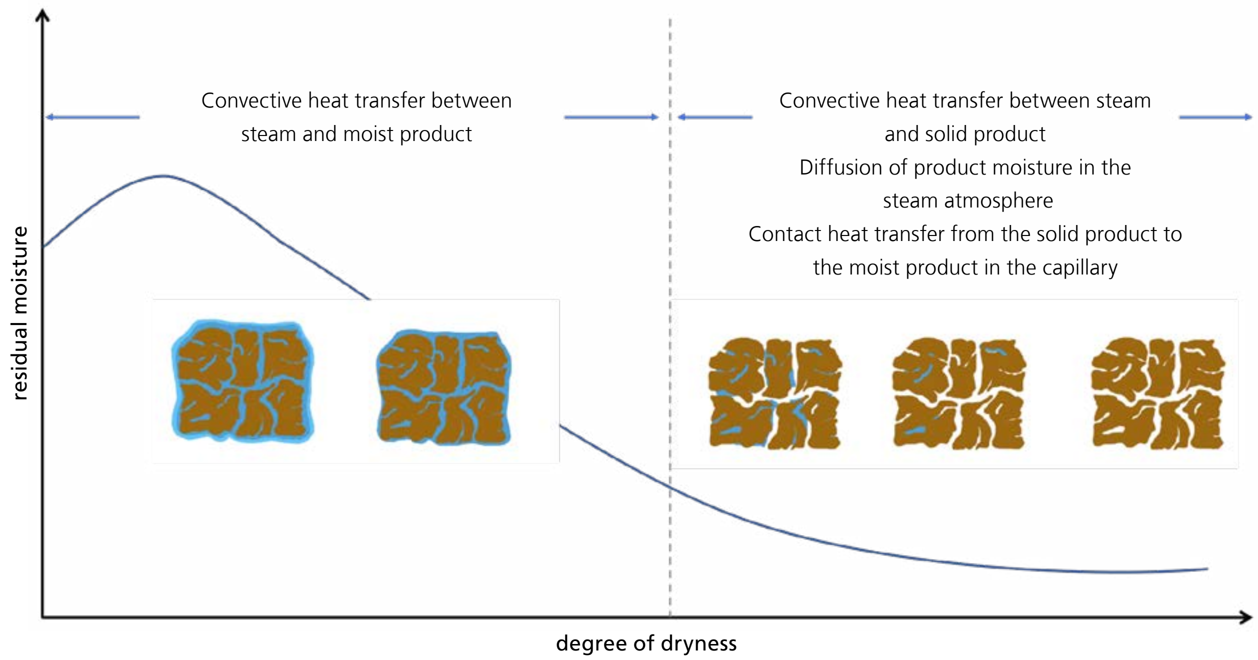
Oxidation processes in the material to be dried, resulting in deterioration of the product quality, are reduced due to the absence of atmospheric oxygen. There is also no risk of explosion, which facilitates ease of operation. The possibility to condensate the excess steam generated during the drying process allows the recovery of volatile substances, for example aroma compounds or organic solvents.



We also offer the design of drying chambers by flow simulations (CFD)

Principle of the superheated steam drying process

The material to be dried is introduced to the superheated steam atmosphere where it is supplied convectively with heat. This causes the moisture to evaporate. Through the uptake of vapor released from the material, the volume of the superheated steam increases, while its temperature decreases without changing the state. As superheated steam is recirculated and reheated in a closed loop to elevate the temperature to the desired level, evaporated moisture becomes excess steam and is carried off along with volatile compounds from the drying chamber. Generally, the working temperature of superheated steam drying is between 130 and 200 °C.



- The initial temperature of the material is about 20 °C. Because of the temperature difference between steam and product, the steam condensates on the product surface.
- Heat is transferred to the product through convection streams. When the temperature has reached the water boiling point, the surface water begins to evaporate.
- After the water is evaporated, water residues remain in the capillary. Simultaneously, the temperature of the solid product begins to increase, because the water that remained in the capillary evaporated.
- The steam penetrates in to the product and evaporates the water from the capillaries and microcapillaries with the help of the solid product's heat. The capillary and microcapillary water is transported to the steam atmosphere through diffusion. The resistance of the moisture to be transported through the steam is smaller than if the drying medium was anything other than water.

The system concept

The system is hermetically closed at the top, but is atmospherically open at the bottom. With a selectively regulated discharge of excess steam, the boundary layer between the phases of superheated steam and ambient air is controlled to prevent the loss of recoverable energy to the environment. Generally, the excess steam at the temperature level above 100°C, which contains virtually the quantity of the heat supplied for drying, can be utilized in other processes in the plant (or be used as process steam). This means that a higher overall energy efficiency of an industrial plant can be achieved.

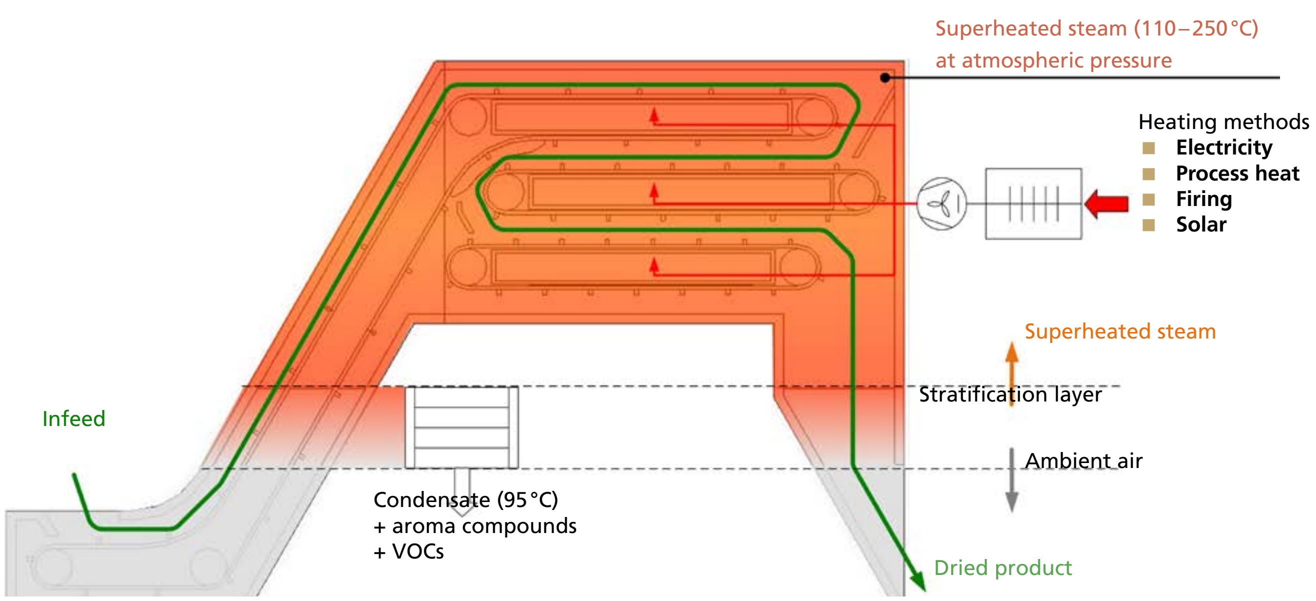
Energy recovery can be conducted e.g. by means of condensation, which allows volatile organic compounds (VOCs) to be condensed out with the excess steam. These condensable organic substances can be further separated by simple decantation and the VOCs are made available as recovered material or value-added product. The use of superheated steam and thus the absence of oxygen permits an inert drying process. This prevents oxidation of the product and significantly reduces the risk of explosion. Moreover, the material to be dried can simultaneously be hygienized by specific adjustment of the temperature and the drying time.

The energy efficiency can be increased by coupling the dryer with other processes, where heat waste is available. The advantage of having water steam, is that the heat capacity is twice larger than of hot air. That means, that the heat transfer is better considering the same amount of mass and the same temperature difference. Due to this thermodynamic advantage, the system can be also coupled with heat waste recovery technology like a heat pump or an organic Rankine cycle.

Free choice of conveying techniques

The conveying system must be designed to cope with steam condensation, but all conveying techniques (rotary drum dryer, screw dryer, spiral dryer, conveyor belt dryer, spray dryer, etc.) can be adapted for use in the drying process in continuous and batch design.

Schematic representation showing the integration of drying with superheated steam into the system



Test equipment

With several laboratory-scale and pilot-scale units, superheated steam drying processes for different materials can be tested, documented and demonstrated. We offer customers from many branches of industry a broad range of services and joint developments. The product – with its specific drying characteristics – determines the design and customization of the dryer. Through trials and practice-oriented approaches, scientists, engineers and technicians design and develop the right solution for individual clients.

Available test equipment

Batch dryer

For a first impression with the product, we recommend tests in the batch dryer. These tests give you a first reference of the operation parameters suitable for the product. The plant consists of a cylindrical chamber, where the sample is introduced from the bottom to the top. The plate, where the sample is deposited has three temperature sensors, one for the steam atmosphere and two for the sample. This dryer also has an inspection glass, which can be used to view the product during drying. This also provides the possibility to record the drying process to document the tests.

Technical data

- Feed capacity: 100 to 1000 g
- Temperature range: 120°C to 230°C
- Product transport: lifting plate
- Plant heating power: 3 kW
- Max steam velocity: 3.5 m/s

Continuous belt dryer

The laboratory-scale belt dryer represents industrial equipment on a smaller scale. The unit is operated as a continuous convective dryer. The product to be dried is transferred on a perforated steel belt (apron), where a stream of superheated steam is passed through. It has four drying sections that can be controlled independently of one another. Parameters such as residence time, temperatures and flow velocity can be adjusted individually to suit the product.

Drying trials can be carried out with this unit, simulating the full-scale production in smaller quantities. The achievable throughput rates depend to a large extent on the characteristics of the product to be dried.

Technical data

- Feed capacity: 6 kg/h to max. 30 kg/h
- Temperature range: 120 to 250 °C
- Product transport: conveyor belt
- Plant heating power: 20 kW
- Max steam velocity: 4.5 m/s

Spiral dryer

Technical data

- Feed capacity: 5 kg/h to max. 15 kg/h
- Temperature range: 120 to 250 °C
- Product transport: conveyor spiral
- Plant heating power: 4 kW
- Max. steam velocity: approx. 4.5 m/s

Reference data

Foodstuffs

Considerable reductions in time have been achieved in the field of foodstuff drying. For example, in the drying of apple chips, the retention time was reduced by 90 percent from 8 hours to 50 minutes without any loss of product quality. Also in the case of pre-processed food products for potato-based snacks, the drying time was reduced by more than 90 percent (from 7 hours to 30 minutes).

Hygienization

Based on systematic test trials we were able to show that superheated steam drying is also suitable for the hygienization of foodstuffs. The microbial load of mushrooms and bell pepper artificially contaminated with E. coli cells and Bacillus endospores was reduced by 7-log stages. Other products that have been tested and studied are tea ingredients (e.g. ginger and juniper berries), bananas, coffee and cocoa beans, fish and shrimps, onions, orange peels, dough for noodles and bread crumbs.

Fodder and pet food

The retention time for various types of fodders and pet foods has been reduced from 35 to 10 minutes. In this study, the superheated steam drying was operated at a temperature 10 °C lower than the currently employed hot-air drying process. The process optimization also results in a lower specific energy consumption.

Mineral raw materials

When drying bulky minerals, a reduction in retention time of 30 percent and energy savings of 40 percent were achieved compared to the existing hot-air dryers. This permitted a reduction of the overall size of the dryer by one third or a corresponding increase of the throughput capacity.

Construction materials

In an initial series of trials on a laboratory-scale belt dryer, the retention time was reduced from 4 to 6 hours to less than 3 hours. This resulted in a time reduction of 25 to 50 percent.

Biogenic waste products

In addition to reducing the energy consumption by over 30 percent, superheated steam was successfully used at laboratory scale to decrease greenhouse gas emissions during drying of sewage sludge. Ammonia and volatile organic acids were identified in the condensate and recovered as secondary raw materials for the production of the mineral fertilizer (e.g. ammonium sulphate). Also, investigations of fermented residues (e.g. anaerobic digestate), manure and algae were carried out by drying with superheated steam with the aim of recovering recyclable materials.

Further new applications

Together with industrial partners, Fraunhofer IGB is further developing the process to extend the use of superheated steam beyond the drying process, enhancing its application in other thermal and thermo-chemical processes. Due to the many advantages of the superheated steam technology, significant progress has already been made:

Roasting

Roasting is the heat treatment of plant-based foodstuffs such as nuts, coffee and cocoa beans, cereals and grains, in which fundamental physical and chemical changes take place in the structure and composition. These result in browning and the development of aromas and flavors.

Superheated steam has already been used and tested as roasting gas for roasting coffee beans at the laboratory scale on a vibrating fluid-bed dryer. The exhaust gas flow was recirculated and reduced to the technologically possible minimum (50 times less exhaust gas flow compared to hot-air roasting), thus only the gas released from the coffee beans during roasting leaves the closed cycle and is condensed out. The condensate was used to cool the roasted coffee beans, preventing an uncontrolled post-roasting. Since valuable aromatic substances including essential oils were identified in the condensate, we are currently working on extracting these individual substances. On the basis of mathematical calculations 245 W thermal energy is required to roast 1 kg of coffee beans. Roasting with superheated steam almost achieves this theoretical minimum value. The process of roasting coffee beans with superheated steam has been successfully implemented in a vibrating fluid-bed dryer.

Torrefaction

In the superheated steam atmosphere, and thus with the exclusion of oxygen, woody material is treated at temperatures of 200–300 °C. After the water present in the material is evaporated, thermal degradation of lignocellulosic compounds takes place; firstly hemicellulose and then a part of cellulose and lignin. The aim of the torrefaction is to enhance the mass-related energy density and thus the heating value of the raw material, to increase the transport capability and storage stability, and to reduce the mechanical works required for subsequent grinding or pelletizing. The resulting product is considered to be an ideal additional fuel for power stations using coal dust firing as well as a raw material for biorefineries for the production of chemicals. Volatile compounds evolving during torrefaction can be pre-separated and further used as feedstock for the production of chemical building blocks.

Our services

- Scientific assessments, consultations, investigations for tasks related to drying and thermal processes
- Development of specific plant concepts according to the needs of individual clients
- Process layout and specification by an interdisciplinary team with a background of process engineering, plant construction, chemistry, microbiology and electrical engineering
- Feasibility studies: laboratory, technical and pilot plants for test trials
- Estimation of CAPEX and OPEX
- Product-related evaluation of the drying process using a wide range of analytical equipment and expertise
- Design and specification of the process unit and components (basic and detailed engineering), e.g. by integrated combination of 3D CAD design, numerical modeling and process automation of e.g. fluid dynamics and heat transfer with the latest software
- Supporting our clients from the first drying trial to realization of the concept and commissioning of a plant

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