

Fact sheet

Drying in the Chemical Industry

prepared for

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by

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Introduction

Drying in its broadest meaning is the process of removing liquid from a solid material, solution, suspension or melt. It is one of the oldest conservation techniques known to man with applications in almost all aspects of daily life. It is also one of the major unit operations in the processing of particulate materials which make up about two-thirds of the world's industrial output. The majority is produced in the chemical industry, either as an intermediate or particulate product. Drying is energy intensive, currently taking up approximately one quarter of the world's energy output, and presents itself a significant factor in production economics.

The aim of this factsheet is to present concisely the importance of drying and its relation to product quality in the chemical industry; the most common drying technologies; opportunities for energy savings in operation, and to provide an overview on recent trends and innovations.

Importance of drying in the chemical industry

The reasons for drying a solid material or solid-containing liquid are manifold, amongst them for example: Stabilisation or conservation of the solid material; to lower cost for transportation and storage by eliminating unnecessary liquid volume; to remove toxic residuals, for example a toxic monomer in polymer production; to improve the overall handling, for example dry powders generally possess a better flow behaviour than moist ones; requirements imposed by subsequent post-processing of the material; or to create specific

solid structures or textures, e.g. formation of agglomerates, or specific surface structures to achieve maximum active surface area (catalyst production).

In drying usually several constraints have to be fulfilled: The quality of the product after drying has at least to be preserved when compared to the quality before drying. Operation has to be performed with a minimum of investment, operating and maintenance costs while assuring a maximum of process safety, especially the minimisation of fire or explosion risks as well as operating with a minimal environmental impact.

The characterisation of product quality has many aspects, some of them competing. The primary aspect to assess drying performance is the residual liquid content in the material after drying. It may influence the transport and storage behaviour as well as the functionality of the material itself, for instance in the production of heat sealing from plastics. If these contain even spurious amounts of liquid, these will form bubbles upon heating which will in turn not provide sealing at these positions [7]. Another important aspect is the preservation of key components, especially thermal-labile components, which pose a limit on the available set of process conditions. Other product quality aspects are: absence of mechanical damage in the material due to stress formation during drying; ability to re-hydrate the dried material, the creation of a specific inner morphology or porosity; and the limitation of structural changes of the dried material, e.g. change in volume or shape (gels, foams).

Fig. 1 shows different surface structures obtained in fluidised bed spray layering, a combination of spraying and drying to build specific layers on carrier particles. Varying the drying conditions, in this case the temperature of the drying gas (air) and the amount of sprayed liquid, a range of different surface structures from open and rough to closed and smooth can be created. Further examination shows that also the porosity of the formed layer changes with drying conditions [12], i.e. drying can be facilitated for particle formation.

Results from a different particle formation process, spray drying, are shown in Fig. 2. Here, depending on the drying conditions (gas temperature and flow rate), also different internal morphologies are created. The formation of internal bubbles is observed which may, depending on the material's capability to even out mechanical stress, lead to bursting of the particle. Even if the particle does not burst, it may either become a compact or hollow particle, depending on the solid movement in the droplets with respect to the speed of drying [2, 4, 10].

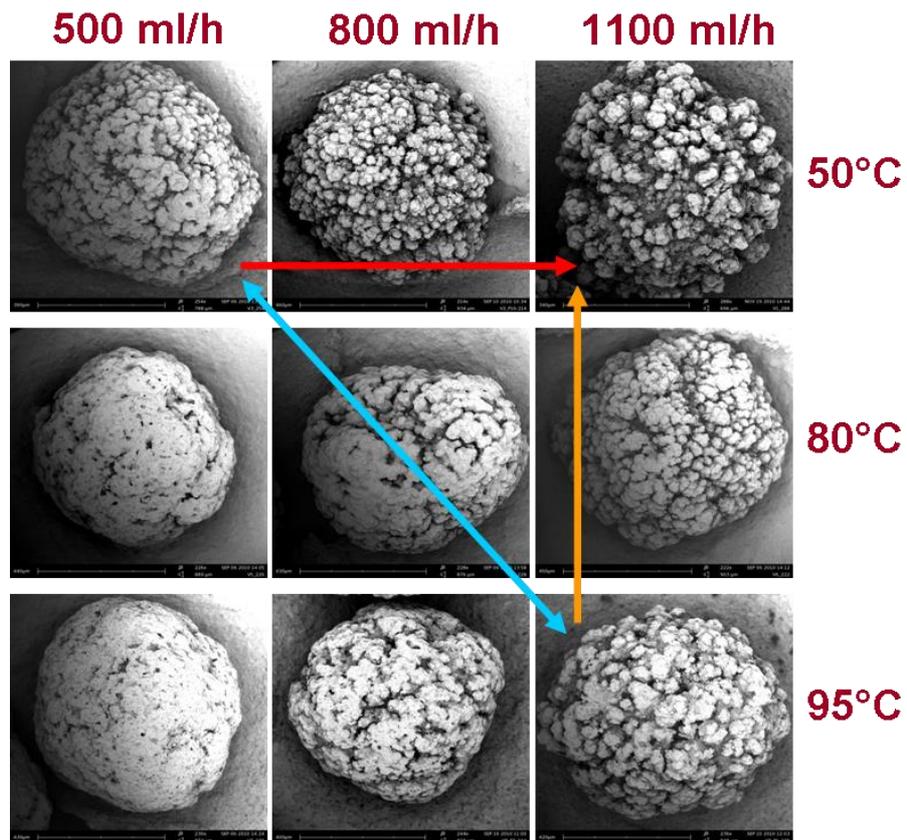


Fig. 1. Effect of gas-side drying conditions on particle surface and layer characteristics in fluidised bed layering granulation. Columns denote the spray rate of material, rows the gas inlet temperature [12].

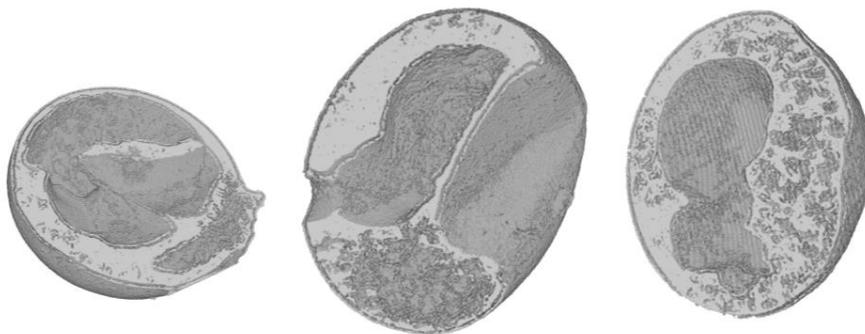


Fig. 2. Different internal particle morphologies created from spray drying of a solution under different operating conditions. From left to right: increasing gas velocity and gas temperature (X-ray tomography images: T.T.H. Tran, Thermal Process Engineering, OvGU).

Common drying technologies

Drying in the above stated sense can be achieved along two routes: Using mechanical forces to separate liquid from solid (“mechanical drying”, “mechanical dewatering”) without significant phase transition of the liquid, or thermally by induction of a phase transition of the

liquid to be removed, for instance by evaporation (liquid to vapour) or freezing followed by sublimation of the (frozen) liquid.

In the following the basic principles of mechanical and thermal drying are presented, as well as examples from chemical industry and the dominant drying equipment.

Mechanical drying

Mechanical drying uses mechanical forces to separate liquid from a solid material. It therefore requires at least two phases (a liquid and a solid phase, e.g. suspension) in application. As mentioned before, usually no significant phase change of the liquid occurs. Mechanical drying can be applied for separation of particles in the size range of some nanometres up to several decimetres. The achieved reduction in moisture content is usually limited to surface moisture. The amount of force that can be applied is restricted by the material properties, e.g. the resistance to mechanical stress, as well as economic constraints.

Mechanical drying is often used in a pre-drying step to remove loosely bound moisture, followed by thermal drying processes to remove the remaining, bound moisture. The main processes used are filtration (cake filtration, screen filtration, deep bed filtration), sedimentation, and centrifugation [1].

In **cake filtration**, the most important filtering process, the separation of the liquid and the solid (filtration from the view-point of the liquid, drying from the view-point of the solid) is achieved by pumping the slurry against a filter medium on top of a filter support. The solid remains on the medium, creating a cake of increasing thickness, whereas the (solid-free) liquid passes. The speed of cake formation and the liquid throughput depend on the pressure difference over the filter medium, the porosity of the formed cake, its compressibility, and the solid content of the slurry. After filtration, the cake has to be washed, dried (either mechanically or thermally) before it can be processed further.

In **sedimentation**, the liquid solid operation is achieved by gravitational force, and depends mainly on the particle size, as well as the difference in density of the liquid and solid. A lower limit for separation by sedimentation is given by the dominance of Brownian motion of the particles at a size of about 10^{-7} m. The performance and required settling times also depend on the formation of particle swarms which reduce the sinking velocity due to interaction of the flow profiles around the particles.

In **centrifugation**, instead of gravity centrifugal force is used to separate the liquid from the solid by rotation of the suspension. It can be efficiently used if the density difference between liquid and solid is (very) small. Due to rotation, forces several ten thousand times larger than the corresponding gravitational force can be achieved. The liquid-solid separation is achieved basically in the way as in cake filtration, with the pressure substituted by the gravitational

force, with the difference that the suspension is rotating. The rotating mass poses restrictions on the apparatus construction as it has to withstand the mechanical stress exerted by the rotating suspension. After drying, the cake has again to be extracted, possibly washed, and dried before it can be processed further.

Thermal drying

In thermal drying the removal of liquid is achieved by induction of a phase change, in many cases a transition from the liquid to the vapour state, and removing the vapour from the solution, suspension or wet solid material. Although the term “thermal” is usually connected with high temperatures, drying can also take place at considerably low temperatures, the prime example being the traditional conservation of fish in arctic air by Inuit. In contrast to mechanical drying, in thermal drying a single phase system suffices with creation of the particulate phase being part of the drying process.

The classification of thermal drying processes is not as obvious as in case of mechanical drying. Currently, over 500 different types of dryers are reported in the literature, some of them in wide use, others specifically designed for one product at one production site. An overview of the different types can be found in [14].

One way to classify thermal dryers is by their heat supply; this yields convective dryers, contact dryers and radiation dryers. These groups can be further divided, for example into sub-groups operating at atmospheric, reduced or elevated pressure, in the presence of an inert gas or vapour, or below the freezing point of the liquid (freeze drying). With respect to installed capacity, convective drying dominates with a share of about three-quarters, followed by contact dryers with approximately 15 per cent share, and the remaining capacity consisting of radiant dryers.

The type of apparatus to choose depends, apart from economic and safety considerations, on the characteristics of the feed and the time available for drying, i.e. in order to dry a solution within seconds to form particles a different technology is required than to dry a pasty feed, a thick film or a particle bed.

In **convective drying**, the heat required for evaporation of the liquid is provided by a heated gas flow, in many applications air, but the heat can also be provided by a flow of superheated steam. First moisture at the surface is evaporated, called the first drying stage, and is purely gas-side controlled. After reaching the material-specific critical moisture content, heat has to be transferred to the interior of the particle to evaporate the liquid, marking the beginning of the second drying period. The vapour is then transferred via diffusion to the surface where it is taken up by the gas or vapour flow. In Fig. 3, a typical evaporation profile in convective drying of solid materials is shown with respect to the average moisture content X . For moisture contents larger than X_{cr} , the evaporation rate is (almost) constant, depending solely

on gas conditions. In the range $X_{\text{hyg}} < X < X_{\text{cr}}$, the evaporation rate is governed also by material-specific mass transfer resistances, leading to lower evaporation rate than in the first drying period. The end-point of convective drying is marked by X_{hyg} , the hygroscopic moisture content: For the given operating conditions (temperature, gas flow, pressure), the moisture content cannot be decreased further. The value of X_{hyg} is given by the sorption isotherm of the material.

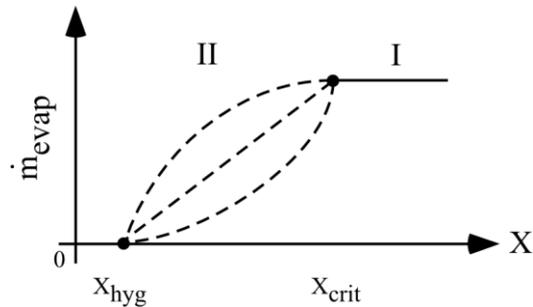


Fig. 3. Characteristic evolution of the evaporation rate with decreasing moisture content X . Dashed lines show possible behaviour in the second drying period with increasing mass transfer resistance in the material (from top to bottom).

In order to achieve high performance, the contact area between the material to be dried, for example particles or droplets, has to be sufficiently large, also a good mixing of the particulate phase and the gas phase is beneficial for dryer operation. Main drying equipment used in convective drying are spray dryers, flash dryers, belt dryers, packed and fluidised bed dryers. Some examples for the use of these dryers in the chemical industry are: drying of ceramics (spray dryer, belt dryer (tiles)); polymers (flash dryers, spray dryers, fluidised beds, often in succession with increase in particle size); salts, phosphates, dyes and gel catalysts (flash dryers); detergents (spray dryer), fertiliser (fluidised bed), drying of cakes obtained from mechanical drying (packed bed, fluidised bed).

Although it may seem counter-intuitive at first, drying in a pure steam atmosphere is possible, as long as the steam is superheated, i.e. the temperature is above the boiling point of the liquid at the given operating pressure. The energy of the steam, given by the difference between operating temperature and the condensation temperature, can be used to evaporate liquid in the material to be dried. Drying with superheated steam offers many advantages; some of them are discussed in the section of limitations in drying operation, and has found widespread application in drying of sugar and coal, and fibrous materials.

In **contact drying**, the heat is transferred from heated surfaces, either apparatus walls or immersed surfaces, to the material. The dominant transfer mechanism is conduction; a gas flow is only used to remove the vapour. They are used to dry a variety of materials, from low-viscous to pasty solutions and suspensions, or fibrous materials. Contact dryers are also operated under vacuum conditions, especially to dry toxic or explosive materials. In that case

the vapour is removed from the dryer, e.g. by a pump, and is condensed outside the apparatus. As in convective drying, the performance of the dryer depends on the contact surface between the heated elements and the material, as well as the temperature difference between the surface and the material. Additional care has to be taken in operation: The material close to the heated surface dries first, reducing its thermal conductivity compared to the wet material, introducing a heat transfer resistance that increases with time. In case of particulate material this effect can be minimised, for example by mechanical agitation of the material, i.e. bringing still wet material to the heated surface and in turn removing already dry material from the heated surface to the interior or top of the bed [13, 15].

Prime example of contact drying is paper drying, where standard dryers produce in the order of 900 metres of paper per minute. Here, a low-viscosity suspension of cellulose fibres (and other ingredients) is usually pre-dried to create a paper film, for instance on a belt dryer, which is then directed over a sequence of steam-heated drums to remove the liquid. The contact time has to be long enough to allow sufficient heat transfer but short enough to avoid sticking of the paper to the drum and risk rupture of the paper film. A similar procedure is used in the drying of textiles.

Other examples are the drying of sewage sludge in paddle dryers (the paddles being moving heated surfaces) or the drying of solutions and pastes, where the material is applied onto rotating, heated drums. During rotation, by heat transfer from the drum surface, the material dries and is scraped off the drum by knives, creating a (pre-)dried particulate product that can be processed further (further drying in a convective dryer, e.g. fluidised bed).

Radiation drying utilises some portion of the electromagnetic spectrum to heat the material to be dried. The heating is achieved by internal dissipation of the electromagnetic radiation by interaction with the molecules in the material. The degree of dissipation and therefore the penetration depth is material specific, with water having one the highest dissipation factors and other materials being almost transparent to electromagnetic radiation, e.g. air, Teflon and some polymers. In contrast to convective or contact drying where the heat is transferred by the surface of the material, radiative heating is volumetric, i.e. the heat is generated directly inside the material. This makes radiative heating a viable option if the thermal conductivity of the material is low, the objects have a large characteristic length (e.g. thickness of a slab of material, e.g. wet wood) or only very low convective heat transfer can take place. The reaction of the material to radiative heating is usually quite fast, however, care has to be taken to avoid local overheating or “thermal run-away”, an effect that is linked to the temperature dependency of the dissipation capacity, i.e. with increasing temperature the capacity also increases which leads to further heating of these locations.

Radiation drying is characterised by the main range of wavelengths used, common examples are microwave drying, (near, middle, far) infrared drying, high-frequency drying (also called

radio-frequency drying or dielectric drying). The radiation can be emitted either using special emitters (microwaves, infrared lamps) using electrical energy, or by sufficient heating of surfaces made from special materials, for example plates of steel or ceramics, where the heating is achieved by burning natural gas. Depending on the temperature, the plates emit a spectrum of electromagnetic radiation that can be tuned to the application.

Main advantage of radiative drying is that the heat can be transferred fast and uniformly to the material. Many applications are found in the treatment of metal coatings (car industry), electronics (drying of etched structures), thin films (polymers), or paper. Main disadvantages are often the required use of electrical energy to emit the desired wavelengths, the design of the field emitters to achieve a uniform electromagnetic field, and required shielding of the apparatus to avoid damages to the environment and human life.

Of course two or more heat supplies can be combined in one drying process or apparatus. Often, microwaves or infrared radiation are used to enhance drying speed, especially in the treatment of porous materials (particle bulk) or in processing of materials that impose a critical time threshold (e.g., foils or paints) for drying.

Limitations in dryer operation

Problems in dryer operation can usually be traced back to capacitive, kinetic or product-related limitations which determine apparatus size, required residence times and allowable process conditions.

Capacitive limitations stem from thermodynamic constraints and are prominently encountered in convective drying processes. The used gas can only take up a maximum amount of liquid per kg of dry gas; the maximum is called the saturation moisture content Y^* . It depends on the saturation vapour pressure, thereby on the gas temperature, as well as the moisture content of the gas. As the gas cools down while evaporating the liquid (starting at point "1"), thermal equilibrium is reached at some point, the saturation point, characterised by the saturation temperature ϑ_s , the saturation moisture content Y^* and a relative humidity φ (the ratio of vapour pressure at a given temperature to its saturation vapour pressure at the same temperature) equal to unity. In adiabatic operation, i.e. neglecting all heat losses, the saturation moisture content and the saturation temperature of the gas can be determined directly from the inlet moisture content and the inlet gas temperature. The most convenient graphical tool for the determination of moisture contents and gas temperatures are psychrometric charts or Mollier diagrams (Fig. 4).

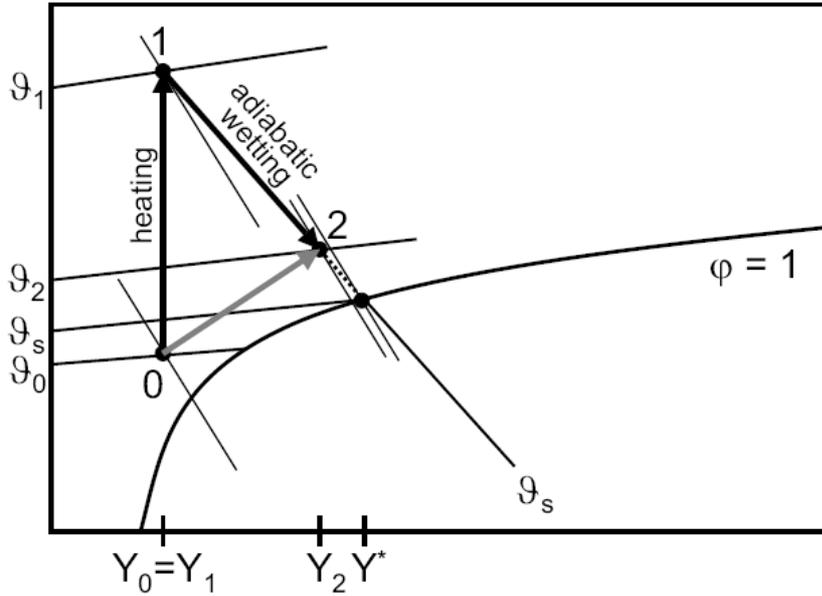


Fig. 4. Exemplary Mollier diagram illustrating the discussed concepts.

The difference between saturation moisture content Y^* and the inlet moisture content Y_0 is the maximum specific uptake capacity of the gas available for (adiabatic) evaporation. Multiplied by the gas mass flow rate yields the maximum evaporation capacity in kilograms of liquid per unit of time, which is for instance in continuous operation the maximum allowable feed of liquid per unit of time:

$$\dot{m}_{\text{evap,max}} = \dot{m}_{\text{gas,dry}} (Y^*(\Theta_s) - Y_1), \quad \Theta_s = \Theta_s(Y_1, \Theta_1)$$

Practically, heat losses are inevitable, i.e. the drying is not adiabatic. This reduces the available uptake capacity and thereby the evaporation capacity of the dryer. Another reduction is due to not fully saturating the gas in operation: If a saturated gas is cooled further, e.g. by contact with cool surfaces (dryer exhaust), the liquid will start to condense, i.e. formation of droplets which may stick to apparatus walls or corrode the material. As a rule of thumb, the outlet gas temperature should lie approximately 10 K above the saturation temperature (Point “2”).

The reduction in evaporation capacity can be counteracted in three ways: Increase of the gas mass flow rate, increase of the inlet gas temperature, or decrease of the inlet moisture content. Of these three, the reduction in inlet moisture content is usually the least effective, as it also changes the saturation moisture content, and it takes special equipment to pre-dry the gas, for example absorption wheels. However, it may be the only option, for instance if drying has to take place at very low temperatures, e.g. for a very heat-sensitive product. Increase of gas mass flow rate and inlet temperature are also subject to constraints, as a too high mass flow rate of gas will at some point start to elutriate material or form dust due to particle-particle and particle-wall collisions, a too high inlet temperature may damage heat sensitive

components in the feed. Furthermore, equipment costs for new fans or heaters as well as an increase in operating costs have to be considered.

Kinetic limitations are heat and mass transfer limitations. Whereas a study of capacity gives an overview on the range of operation set by thermodynamic constraints, kinetics provide the insight on how long drying will take. Fast kinetics usually allows for short residence times and thereby either large throughputs or small apparatuses.

In convective and contact drying, heat transfer is mainly limited by the surface area available for transfer, or the temperature difference which acts as driving force. In pure contact drying, heat transfer is also limited by the increasing dry layer directly in contact with the wall; in that case frequent mixing of the material may improve kinetics.

The heat transfer coefficient usually also depends on the local flow conditions, i.e. at stagnant flow the heat transfer coefficient is smaller than at high gas velocities, meaning that the local flow conditions can significantly contribute to kinetics and this provides a link to apparatus design. Increasing the surface area may improve the kinetics, so some milling of the wet material or fine spray of a solution and thereby increasing the overall surface area may prove beneficial.

Another option, for instance used in fluidised beds, is the immersion of steam-heated surfaces to provide additional heat transfer by contact heating. However, the total surface area is limited construction-wise as the heated surface reduces the dryer volume and also influences the particle and gas flow. Another drawback is fouling on the surfaces, requiring regular cleaning to avoid production safety issues. One way to overcome the drawbacks of steam-heated tubes in fluidised beds is the use of electrically conductive materials, e.g. hollow iron spheres that co-fluidise with the material to be dried [5, 6]. These spheres can be heated by induction using an external electromagnetic field. The main advantages are the comparatively huge transfer area, the good mixing with the material and the capability of self-cleaning by collision. The main drawback is that for the electromagnetic field electric energy has to be used, which limits application to high-valued products.

Heat transfer can also be enhanced using volumetric heating, for example by infrared or microwave radiation, in assistance of contact or convective drying, often increasing the overall kinetics by an order of magnitude. But again, additional equipment and operating costs, i.e. for shielding and generation of the electromagnetic waves, have to be considered in the production economics.

Mass transfer (evaporation) in convective drying is in the first drying period limited by gas-side resistance, i.e. the different mobility of gas and vapour molecules, which is expressed by the inverse of the effective vapour diffusion coefficient. A small diffusion coefficient signals large gas-side mass transfer resistance (different molecules repel each other)

whereas large diffusion coefficients signalise low mass transfer resistance. The diffusion coefficient often shows temperature and pressure dependencies, i.e. a change in these process variables may improve mass transfer. In the second drying period, mass transfer also depends on the material characteristics, for example internal porosity and the path length from the surface to the location of evaporation. Here not only vapour diffusion is important, i.e. the transport to the surface, but also gas diffusion from the surface to the interior of the particles as the gas provides the heat required for evaporation. Again, volumetric heating may improve the situation, as by selective heating local over-pressure is created that yields capillary pumping from the interior to the surface as well as direct evaporation of liquid in the interior.

One option to avoid mass transfer limitations completely is drying in a pure vapour atmosphere. In that case, liquid and gas molecules are identical so that no mass transfer resistance exists. Evaporation is then purely a heat transfer problem. Other advantages are: Easy condensation of excess vapour (simply by cooling, no mass transfer resistance), as well as increased process safety if the vapour is non-ignitable. Main drawbacks are increased plant costs and problems in handling of dust contained in the vapour, especially when re-heating the vapour in closed-cycle operation.

Most difficult to handle are **product-related limitations**, as these are very specific and may even vary between different modifications of one and the same material. Many material are heat-sensitive, meaning that above a certain material temperature changes in the internal structure or composition (partial melting and formation of agglomerates upon particle-particle collision) may occur that will change product properties. This effectively limits for instance the gas inlet temperature in convective dryers as, due to differences in residence time; already dry particles may be subjected to too high temperatures, possibly damaging the material.

Complying to the maximum allowable temperature may decrease the evaporation capacity in a way that it can no longer be adjusted by other means. In that case, intermediate heating will improve the situation: Instead of heating the gas to the temperature required for the uptake capacity in one step, the heating is performed in several steps: In the first step, the gas is heated close to the maximum temperature then it is wetted close to saturation; this moist gas is heated again in a second heater and is wetted again, and so on. In each heating step, an additional increase in uptake capacity is achieved without passing the maximum allowable gas temperature; the number of intermediate heating steps can be obtained directly from the psychrometric chart, following the description. In operation, the additional heaters have to be installed, increasing equipment and maintenance cost.

Another product-related limitation, especially occurring in the handling of polymers (and other macromolecular substances) is the effect of glass transition. These materials can exist in two states, crystals with a long-range order of molecules, and in an amorphous state, where only a short-range order between molecules is present, i.e. the molecules can move inside the

macrostructure. The formation of amorphous structures is kinetically controlled and depends on the material history in the process. Important polymers that can exist in amorphous states are PVA, PVC, PET, PMA, PMMA, PE, and BMA.

Amorphous materials can exhibit a glass transition, taking place at the glass transition temperature T_g . At this temperature, upon heating, the amorphous material changes from a solid and brittle glassy state to a rubbery and viscoelastic state (Fig. 5). The rubber state is bounded from above by the melting temperature of the material. With increasing distance from the glass transition temperature, the viscosity of the rubbery material decreases, simultaneously the diffusivity of the molecules increases, as well as the reactivity. The most critical property, however, is stickiness due to the viscosity of the material at the surface, most pronounced in the range of 15-30 K above the glass transition temperature. It may lead to adhesion of particles to apparatus walls (deposits) or the formation of agglomerates during drying, which not only pose a product quality but also a process safety issue, as deposits may dry out and start glimmering or burning. These problems are for example encountered in spray dryer operation, leading in worst case to fire or dust explosion, damaging the equipment and endangering the safety of operator personnel.

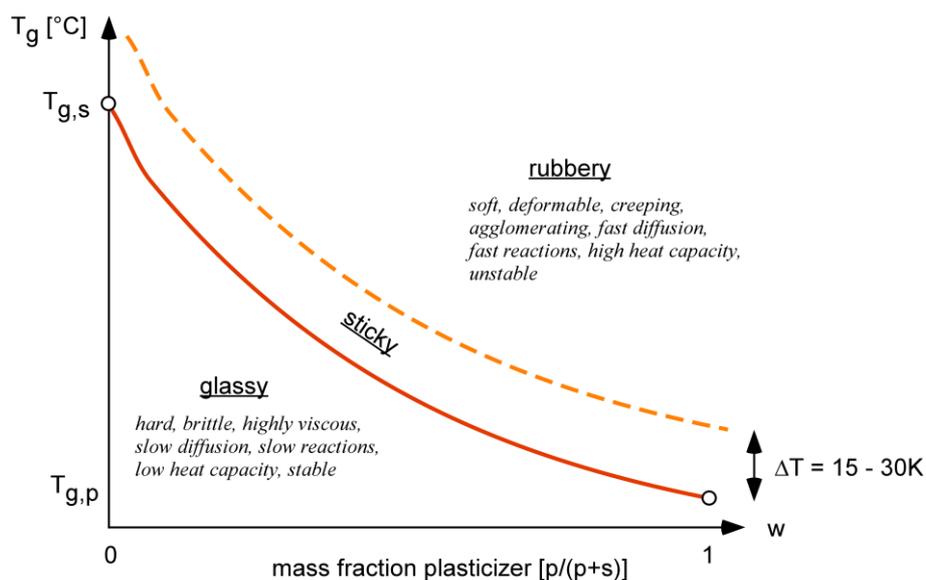


Fig. 5. Dependency of glass transition temperature of a solid (“s”) on the amount of plasticiser (“p”) in the mixture. The slope of the glass transition curve can be parameterised by an empirical constant in the Gordon-Taylor equation.

Glass transition of amorphous materials can be tremendously enhanced in the presence of a plasticiser, a second component that reduces the glass transition temperature of the mixture. For instance, polyvinyl alcohol (PVA) reacts strongly to polyethylene (PE), as does styrene to methylacrylate (MA). The influence can be described empirically by Gordon-Taylor theory which links the glass transition temperature of the mixture to the glass transition temperatures of the pure components and the weight fraction of the plasticiser [3]. A component that

increases the glass transition temperature is called a vitrifier. As another example, carbohydrates (food materials) are very sensitive to water as plasticiser ($T_g(\text{water}) = -135\text{ }^\circ\text{C}$).

Furthermore, drying conditions have to be chosen such that shrinkage or expansion of the material is kept within bounds, posing limits on the heat and mass transfer. This requires information on the internal structure of the material and also its behaviour under mechanical and thermal stress which may lead to crack formation, damaging the product.

Energy requirements and savings

Drying of particulate materials is energy intensive in general, taking up to one quarter of a nation's energy output [8, 9]. Figure 6, for instance, shows the relative distribution of energy consumption in the Netherlands with more than one third spent in manufacturing. Available data from other European countries, e.g. the UK, shows that approximately ten per cent are used for drying operation in the various production and manufacturing areas. The distribution of energy consumption for drying varies strongly, as shown in Fig. 7. Collecting chemicals, textiles, paper, cement and timber drying into the group of chemicals, up to two-thirds of the energy is consumed in the chemical sector. Combining these numbers gives an estimate of about 240 PJ spent annually on drying of chemicals in the Netherlands. Improving the efficiency of energy consumption in this area is therefore not only desired from an economic, but also from an ecologic point of view within the unified European task of reducing the carbon footprint of production under the various UN climate protocols, e.g. Kyoto protocol.

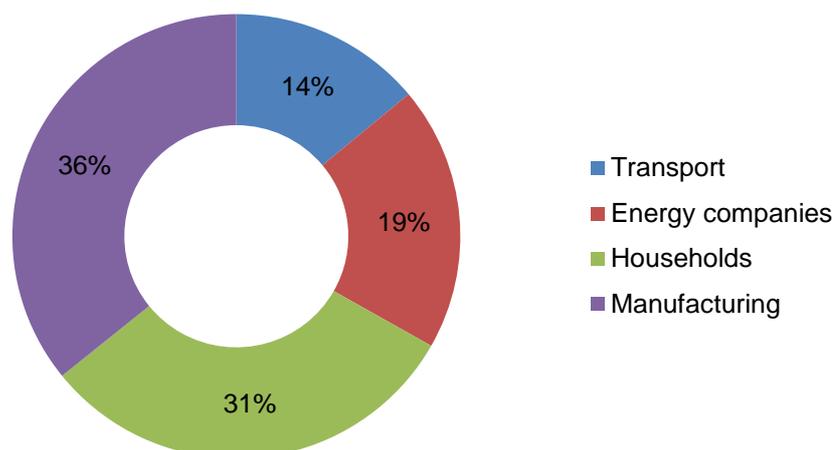


Fig. 6. Relative distribution of energy consumption in the Netherlands, with a total consumption of 3500 PJ (1 PJ = 1,000,000 GJ, Dutch Energy Report 2011).

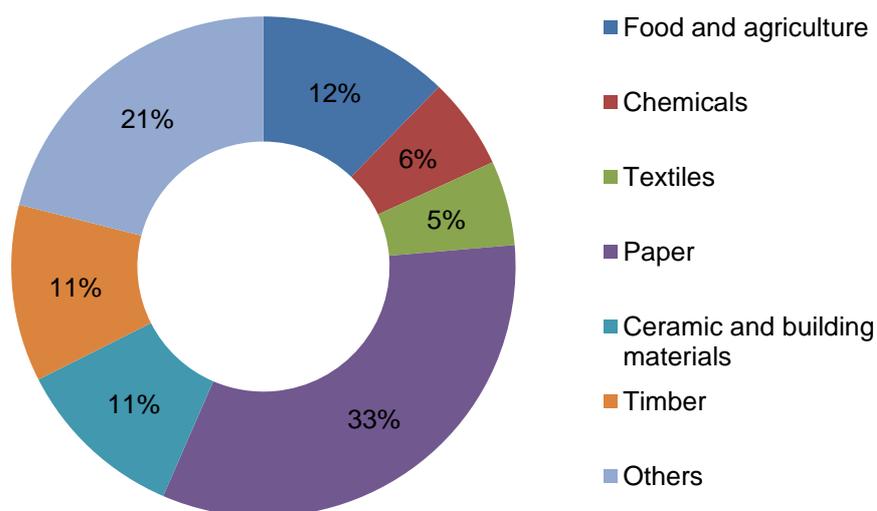


Fig. 7. Relative energy consumption for drying in various fields of production.

Energy requirements for drying vary significantly with the applied principle (mechanical or thermal) and the used equipment.

In mechanical drying, the energy consumption is due to operation of pumps to provide the required pressure difference over the filter, or to achieve the centrifugal force for separation. The specific energy demand for the different mechanical drying apparatuses ranges from 0.1 to 200 kWh/(m³ filtrate) or, taking water as the liquid to be removed, up to 720 kJ/(kg liquid). The lower value corresponds to simple cake filters whereas the higher value corresponds to ultra-centrifuges for the separation of bio-molecules from liquids.

In thermal drying, the theoretical minimum energy requirement to achieve phase transition is given by the specific evaporation enthalpy of the liquid. For example: Water has at 0 °C a specific evaporation enthalpy of 2500 kJ/(kg liquid), ethanol of 841 kJ/(kg liquid) and propane of 356 kJ/(kg liquid). The actual specific requirement for evaporation is significantly larger and depends on the overall efficiency of the dryer, which may take values as low as 20% or as high as 90%. A typical value for the efficiency of a convective, e.g. a spray dryer, is about 45%, meaning that in operation more than twice the specific evaporation enthalpy has to be supplied to achieve evaporation of one kg of liquid.

Comparing this with the values reported for mechanical drying immediately leads to the conclusion that it should be considered in all drying operation as pre-drying step, provided that the feed is a suspension.

The energy cost of drying poses an economic challenge, especially if the product is a low-value bulk commodity. Fig. 8 shows the price development in Germany for the three main

heat and energy sources used in drying: natural gas, electricity, and steam. The data is normalised with respect to the year 2010 (100%). Although there are fluctuations and differences between the three, on a large scale, the prices are increasing. Another aspect to consider is that the absolute prices also differ, i.e. the cost of one kWh of natural gas is different than for one kWh of electrical energy.

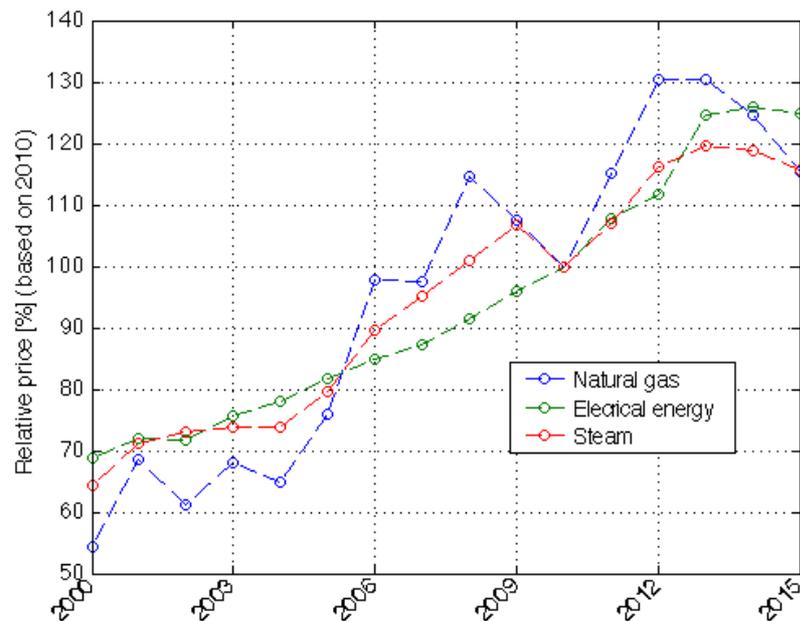


Fig. 8. Relative price development of heat and energy sources in Germany, normalised with respect to the year 2010 (source: DESTATIS, 2016).

The difference stems from the required transformations of the primary energy (fossil or nuclear) to the usable energy form (natural gas, electricity), and can be expressed by government-normed primary energy factors. The primary energy factor of natural gas, for instance, is 1.1, i.e. a ten per cent overhead is created by the transformation from the fossil fuel to the natural gas that be burnt to create the desired heat. For electricity, the chain of transformations is considerably longer and the efficiencies of the transformation steps have to be considered, leading to a primary energy factor of 2.6, i.e. only approximately one third of the primary energy is converted into electricity. As a rough estimate, the primary energy factor of an energy or heat source times the price of natural gas gives the market price. For example in 2014 in Germany, the price for natural gas was 3.54 €-cents/kWh whereas one kWh of electricity did cost 13.76 €-cents.

These developments require dryer manufacturers and operators to find new ways to improve dryer efficiency and energy usage while preserving product quality and complying to environmental obligations. Following Kemp [8], energy reduction methods can be classified into several groups:

- Reduction of thermal energy requirement by mechanically drying the feed: As mentioned before, specific energy consumption in mechanical drying is typically significantly lower than in thermal drying. Removing loosely bound liquid from the material mechanically and only removing bound water thermally may significantly reduce thermal energy requirement. However, drying of the filtered material (cake) may prove a difficult challenge, also the product characteristics may change, especially if the material is compressed during mechanical drying.
- Increasing efficiency by reduction of heat losses, optimising total air flow and operating times (esp. in batch operation): Reduction of heat losses can be achieved by thermal insulation of the apparatus, but may prove a significant cost factor if the apparatus surface area is large. However, good insulation will additionally reduce the occurrence of cold spots in the apparatus, reducing the danger of condensation of wet gas flows. Optimising total air flow, i.e. avoiding excessive air flow (which needs to be heated) can further reduce the costs, however, the capacitive constraints have to be met. Optimisation of operating times is very product-specific and refers to reduction of drying time to the minimum time required, for example to avoid over-drying or excessive heating. This proves in practice to be very challenging, especially if the feed conditions vary significantly.
- Heat recovery within the dryer between hot and cold streams: Heat recovery from gas streams in the dryer, for example recovery of exhaust heat to heat inlet air, which is expected to save up to 30 PJ annually in the Netherlands alone, is usually very difficult because of the low temperatures of the outlet stream and small difference between inlet and outlet temperature. Sufficient heat transfer would require large heat transfer areas (large apparatuses) which again have high costs for equipment and operation.
- Heat exchange between dryer and other process equipment: This approach proves to be quite challenging in hot gas convective drying as the outlet temperature of the gas is usually too low for other uses. If, however, superheated steam is used for drying, then the exhaust steam (temperature still above 100 °C at atmospheric pressure) can be used either directly in other equipment or in a closed-loop system be recompressed and re-circulated.
- Use of heat pumps to transform waste heat into heat useful for dryer heating: Heat pumps can be used to lift low temperature heat to higher temperatures that can be used for dryer heating subsequently. In order to achieve this temperature lift, mechanical or electrical work (e.g. compression) has to be supplied to the medium. Heat pumps are characterised by the coefficient of performance (COP) which expresses the “lifted” heat per unit of supplied power. Generally, the COP decreases with increasing temperature lift. Taking into account the conversion factors from primary energy to usable energy and heat (e.g. electricity), a minimum COP of three is required. However, in terms of economics, i.e. taking into account the costs for the equipment,

its operation and maintenance, COPs larger than five are required. If electrical energy is cheap than also lower COPs are acceptable, but even then use of heat pumps is in most cases only economically feasible for high-valued, high-quality products.

In order to improve the situation, not only the energy requirement of the dryer but the whole production system needs to be considered. One tool that proved particularly suited for energy integration and process intensification is pinch analysis [8] which identifies the correct temperature levels of arbitrary flows in the plant at which heat recovery can be performed with a net gain. Other ways to intensify processes have already been discussed in the section on kinetic limitations, e.g. the immersion of heated surfaces.

Another option is the use of mathematical optimisation techniques to design heat exchanger networks in such a way that energy recovery is most efficient. In Moejes et al. [11], an application of this approach is shown to closed-loop spray drying operation and significant energy recovery is reported, yielding a reduction in overall energy consumption of the process by 60%. The principle used can be readily transferred to spray-drying operation in the chemical sector, e.g. in the spray drying of ceramics. Comparable energy savings would on one hand significantly reduce the ecologic influence of production, and on the other also provide a significant boost in the economics of the process.

In general, it can be stated that with ever increasing computational power and the availability of detailed process models, energy recovery by structural optimisation of drying operation becomes a viable option, providing means to achieve not only better products but also to achieve international climate goals.

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Further Reading

Recent advances in the area of drying and drying-related particle formulation and its application in the chemical industry, as well as coverage of the topics process intensification and energy savings are reported in a variety of scholarly journals, for example *Powder*

Technology (Elsevier), Advanced Powder Technology (Elsevier), and Drying Technology (Taylor & Francis).

Comprehensive references are furthermore the five-volume book series “Modern Drying Technology” (edited by E. Tsotsas and A.S. Mujumdar, VCH-Wiley, Weinheim), the “Handbook of Industrial Drying” (edited by A.S. Mujumdar, CRC Press), the “VDI Heat Atlas” (Springer Verlag), and the chapter “Drying of Solids” in Ullmann’s Encyclopedia of Industrial Chemistry (edited by B. Elvers, VCH-Wiley, Weinheim), as well as references given therein.