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Abstract

"Drying" is a widely used, energy intensive process, but it is difficult to evaluate generic efficiency measures. This must be done case or system specific. The present report is summarizing possible measures to increase energy efficiency in drying processes which in principle can be applied for all kinds of dryers and products.

Around 85% of all industrial dryers are based on the drying agent air. Superheated steam drying and pulse combustion drying were identified as possible replacement technologies to increase the energy efficiency with 20% to 45% respectively.

Recovery of excess energy through heat pump drying or mechanical vapour recompression has the potential to save between 50% – 75% primary energy consumption in drying processes. The concept is well known and industrially implemented for low temperature drying (<30°C). The R&D challenge is to design suitable heat pump drying systems for high drying temperatures.

HighEFF

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1 Introduction

This project memo is a part of the work package "Heating, cooling and drying" (RA3.2) from the FME HighEFF. The focus of the work package in general is energy efficient solutions for heating and cooling applications and is investigating mainly novel heat pump systems and applications. "Drying" was included in this work package, since it was identified as one of the cross-sectional processes in which novel heat pump solutions can be applied, see Table 1.

The concept of "drying" in the HighEFF sense is a process which evaporates water through the supply of thermal energy. The evaporated water is waste heat for the process since the temperature level will be lower compared to the temperature requirement of the supplied thermal energy. With this definition **the drying concept can be applied for processes like distillation, evaporation, cooking, pasteurization and sterilisation** as well. Estimates evaluate that drying is responsible for 15-25% of the overall global industrial energy demand in developed countries and efficiencies in food drying can be as low as 10%, with 35-45% being the average [1]. Hence, there is a high potential for energy savings, and the aim of HighEFF is to evaluate and introduce concepts for energy recovery and increased energy efficiency for these processes.

The Handbook of Industrial Drying[2] gives at least 15 different dryer types and identifies more than 20 different industrial drying sectors, which makes it rather difficult to generalize drying technologies. For every sector a certain drying process is characterized by the type of dryer, the quality of the final product, additional needed processing, the ease of handling, sanitation, cost/energy effectiveness, and investment. However, the basic principle of drying is the same as it used to be thousands of years ago, and the most common dryer type is based on convective drying.

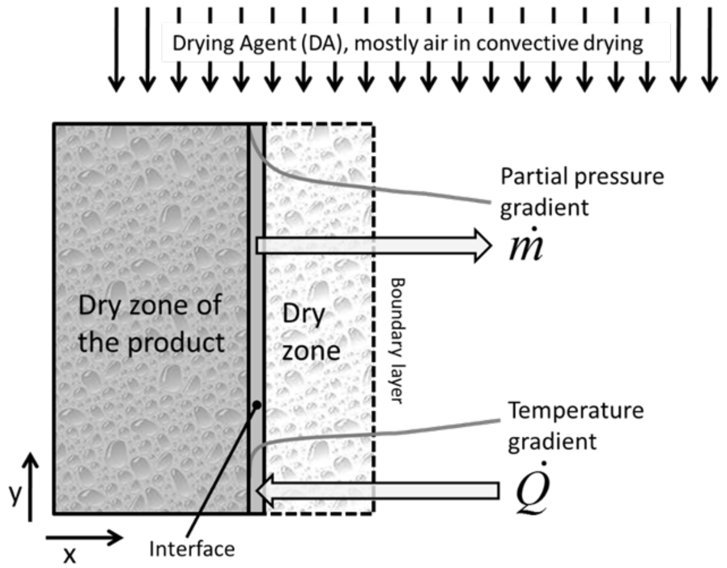
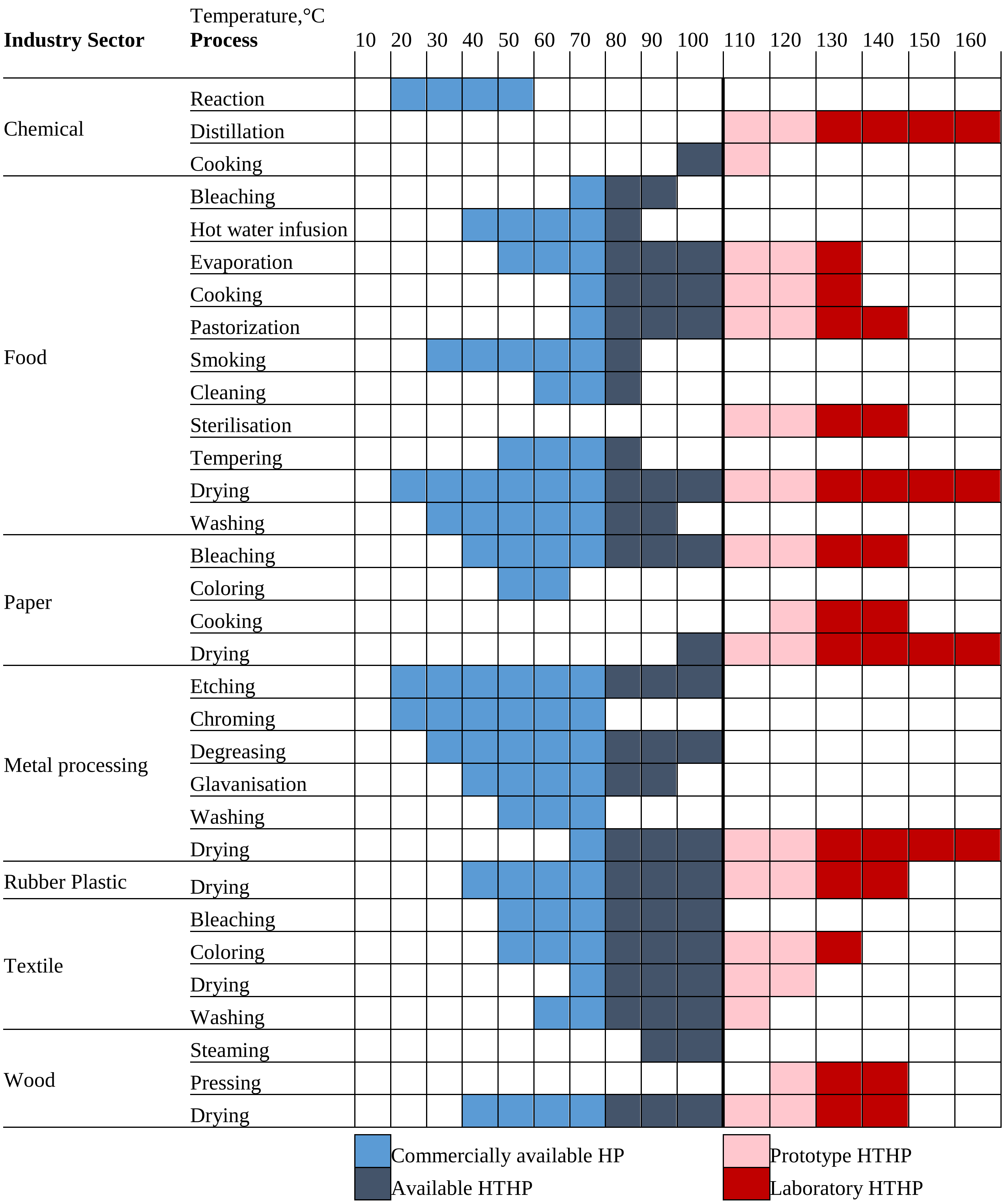


Figure 1: General heat and mass transfer in convective drying of products.

[1] Mujumdar, A., 2007. An overview of innovation in industrial drying: current status and R&D needs. Transport in porous media 66, 3-18
[2] Mujumdar, A.S. (2007). Handbook of Industrial Drying. Boca Raton, Fla., Taylor & Francis

Table 1: Identified thermal process for the application of industrial heat pumps (based on [3]).



[3] Wolf, S., et al. (2014). Analyse des Potenzials von Industriewärmepumen in Deutschland (in German) Forschungsbericht. Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung

2 Drying Energy

In drying technology, the term convective drying is used to indicate when heat and mass transfer are due to the temperature and pressure gradients, respectively, between the drying agent (DA) and the drying product. The molecules that are moved (convected) are the water molecules that diffuse into the drying agent. Convective drying, based on air as the drying agent, is the mostly used drying process, and globally more than 85% of all dryers are of a convective air-drying type.[4] However, also other drying agents like superheated steam are used in convective dryers, because of improved thermal properties and/or drying potential.

The purpose of the drying agent in convective drying is to supply the necessary energy for the evaporation of the moisture from the product, capture the evaporated water and remove it from the drying system. The speed at which the moisture is removed is commonly referred to as the drying rate.

The first drying stage is a function of the heat transfer between the drying agent and the water if the moisture of the product is present as surface water. In this case, the drying rate is constant up to the point when a dry layer develops in the product. The (growing) dry layer poses an additional resistance to the heat and mass transfer and results in a reduced drying rate, as illustrated in Figure 1 and Figure 2.

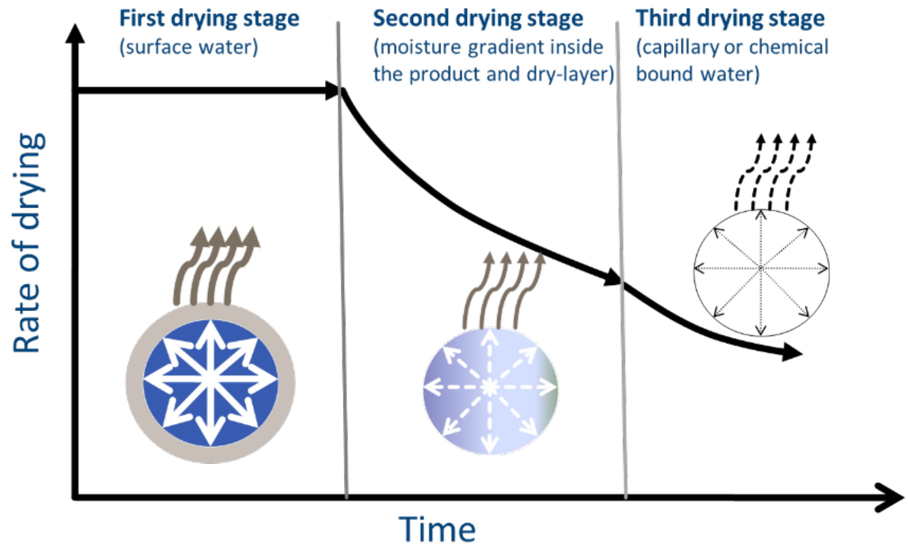


Figure 2: Characteristic different drying stages with constant and falling drying rate periods.

For batch dryers this normally results in falling drying rates with the drying process, the so called second drying stage. For continuously operating dryers, the drying rate of the system appears constant even when the product is in the falling drying rate period.

In general: the mass transfer in drying is achieved by evaporating the moisture of the product and let it diffuse into the drying agent. In other words, the water to be dried out needs to undergo a phase change from liquid to vapour in order to be removed from the product. The necessary energy for this phase change is the evaporation energy, which is the minimum required thermal energy to enable convective drying. For water, the evaporation energy is 2258 kJ/kg (at 100°C) or 0.627 kWh/kg. This is the theoretical minimum required thermal energy for any convective drying system. Real operational dryers require additional energy to overcome heat and mass transfer losses, product specific moisture binding resistance, thermal heat losses and

[4] Atuonwu, J.C., et al., Reducing energy consumption in food drying: Opportunities in desiccant adsorption and other dehumidifaction strategies (2011)

others (see Figure 3). The sum of all required and supplied thermal energies are commonly referred to as the drying energy.

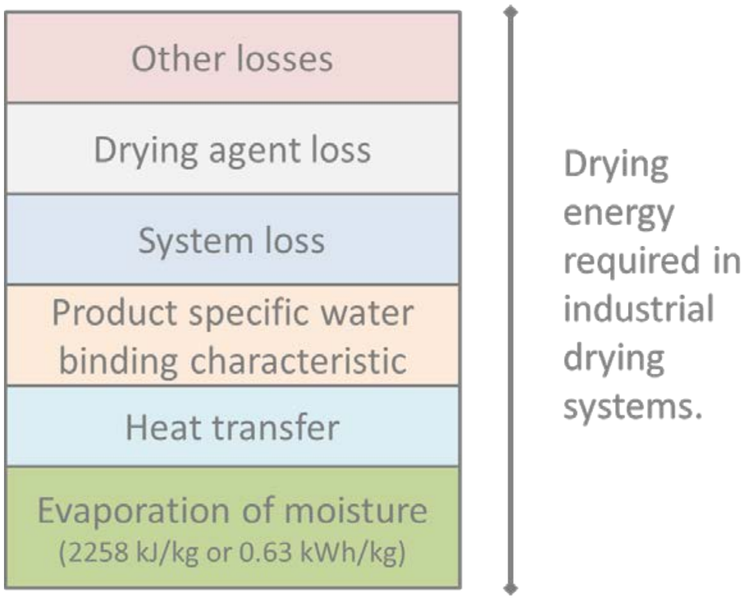


Figure 3: Drying energy in real-life convective drying systems.

The drying energy in convective drying systems is supplied as **sensible heat by the drying agent**. In most drying applications this energy is supplied by simple heating devices which are used to heat up the drying agent so that it contains the necessary sensible heat before drying. The sensible heat of the drying agent is then used to dry the product. The drying agent is consequently cooled down during convective drying and the sensible heat is transferred into water vapour and removed from the system. In other words, the drying agent is hot and dry when it enters the drying system and cold and moist when it leaves the drying system. In order to reuse the drying agent again at the inlet of the dryer, the drying agent needs to be reheated and combined with a supply of heated fresh drying agent as needed. **It is important to notice that the supplied drying energy, *i.e.*, the sensible heat, leaves the system and can be recovered in the form of water vapour in the drying agent.**

With respect to energy recovery it is only possible to recover and reuse the thermal energy from the evaporation of moisture; basically the green area of Figure 3. The additional drying energy is necessary to keep the dehydration process running. However, this energy is lost in that sense that it cannot be recovered from the drying agent. It leaves the drying system as heat losses, heat and mass transfer losses or by the product itself. In order to reduce the specific energy consumption of a drying system it must therefore first be evaluated if and how these losses can be reduced. As an indication it can be said that the drying system is quite energy efficient once the specific energy consumption is reduced to below 1 kWh per kilogram of evaporated/dried water. At this point further reduction in specific energy consumption can only be achieved by high efforts. The lowest achievable specific energy consumption will be around 0.7-0.8 kWh/kg for the drying unit. In order to reduce the system efficiency further it will be necessary to extend the system boundaries and include e.g. heat pumps or other energy sources as a part of the drying system.

3 Superheated steam drying

As outlined above, around 85% of all drying system are based on convective drying using hot air as drying agent. This has most likely historical reasons. The function of the drying agent is to deliver the thermal energy needed for evaporation and to remove the moisture from the product. The thermal properties of air are far from optimal for this purpose. The quality of the product is significantly altered by the drying process, since it is exposed for a long period of time to hot air, which results in product degradation (e.g. oxidation).

Superheated steam is in many ways a better drying agent than air due to its physical properties, heat and mass transfer, as well as more efficient penetrability. The heat transfer coefficient of steam is twice of that of air. The viscosity (penetrability) of steam is at the same time almost half of the viscosity of air. Superheated steam drying therefore has the potential to shorten drying time and energy demand by 20-30% compared to air drying. The advantages of substituting air with superheated steam (SHS) drying are summarized in Figure 4.

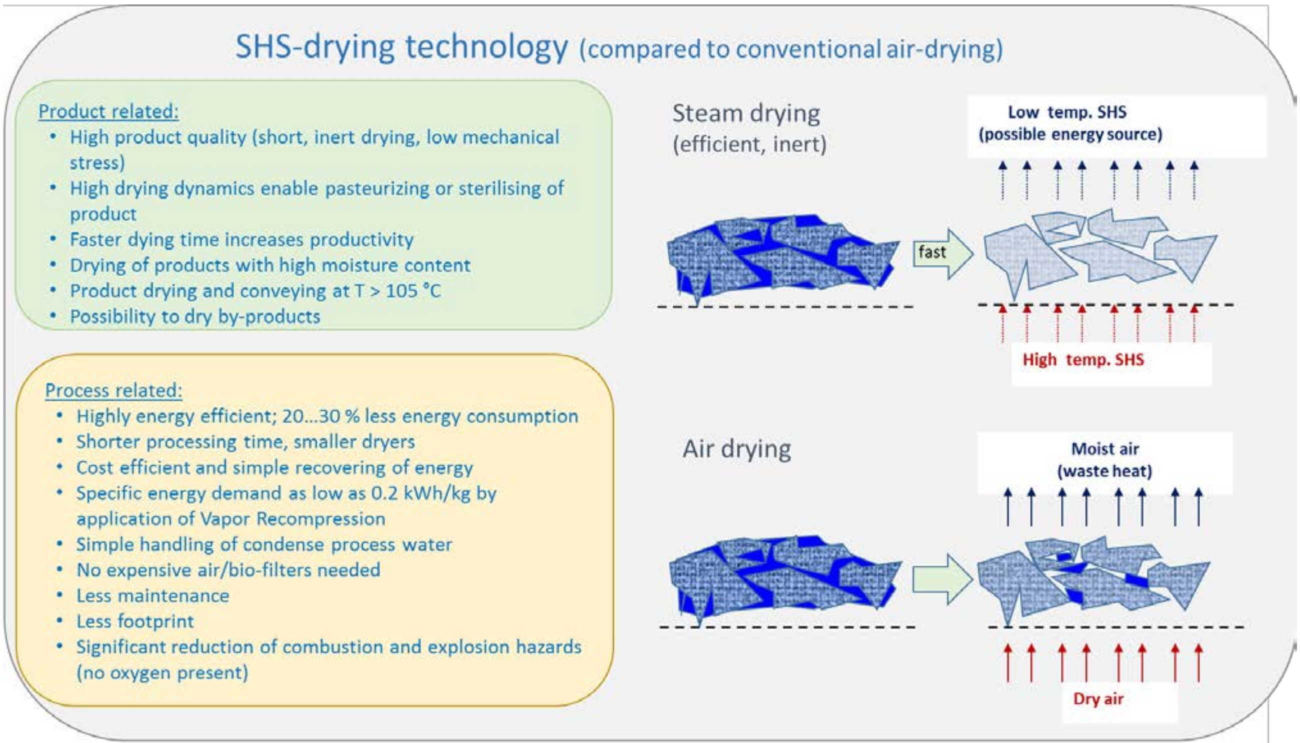


Figure 4 Potential (Hypotheses) of the superheated steam drying technology

Convection drying is very detrimental to nutritional and nutraceutical characteristics of the product. This is due to usually very extended drying times and exposure of the product surface to oxygen. This in turn leads to enzymatic and non-enzymatic oxidation of the product. Superheated steam drying applies higher temperatures, leading to reduced drying time. Industrial investigations have shown that the overall quality is higher compared to conventionally dried products. Superheated steam drying is by default inert and consequently no oxidation appears. Further, the product is sterilized during the process, thus removing the problem with microorganisms completely. The shorter processing times (up to 30%) positively impact the overall production efficiency of the processing plant and reduces the dryer size.

3.1 Energy aspects of SHS drying

The energy efficiency of the drying process can potentially be reduced by 20-30%, as outlined above. This will however depend on the used dryer type as well as drying characteristics of specific products. Simulation tools can verify this potential to a certain extent by comparing the heat transfer coefficients and density of the air and steam for a given drying process (see Table 2). Through HighEFF the potential of superheated steam is so far not verified by experiments or simulation; this will depend on whether an industry partner is interested in such a verification for a specific product or case. Naturally such a partner specific study would be done through a spin-off activity.

Table 2: Overall heat transfer coefficient and viscosity for superheated steam and air[5]

	Temperature	Steam	Air
Heat transfer	100 °C	2.04 kJ kg^{-1}	1.01 kJ kg^{-1}
Heat transfer	150 °C	1.98 kJ kg^{-1}	1.02 kJ kg^{-1}
Viscosity (~ mass transfer)	100 °C	12.3 kg s^{-1}m^{-1}	22.0 kg s^{-1}m^{-1}
Viscosity (~ mass transfer)	150 °C	14.2 kg s^{-1}m^{-1}	24.0 kg s^{-1}m^{-1}

Using SHS as drying agent results in excess steam of colder SHS. The drying energy can be recovered quite easily by conventional steam condenser technology. From the energy point of view this is the main advantage of SHS drying. This excess steam can directly be used in Mechanical Vapour Recompression system (described in chapter 4), hereby reducing the specific energy consumption of a SHS-drying system potentially to 0.2 kWh/kg (up to 70% energy saving potential).

3.2 Product aspects of SHS-Drying

Drying with SHS is naturally done at temperatures above 100°C and the product needs to tolerate this temperature. However, it has to be distinguished between product temperature and drying temperature. Exposing a wet product at atmospheric pressure to superheated steam will result in evaporating the water at 100°C. The product temperature will therefore not be higher than 100°C even if the temperature of the steam is >150°C.

To avoid condensation on the product surface it is on the other hand necessary to heat the product close to 100°C before entering the dryer. After drying it is then also necessary to cool the product again to ambient temperature. This is an additional energy demand for the production which has to be integrated in the system.

During drying the product normally undergoes certain structural and quality changes. It has to investigated for each product individually if these changes in SHS drying are acceptable. However, SHS is inert drying and for certain food products a quality increase has been documented.

3.3 Dryer design for SHS

Most industrial drying systems are designed, constructed and optimized for air drying. By substituting air with SHS the dryer must be re-designed:

1. The construction must ensure that the SHS can be circulated through the dryer and a heating element. This is similar to an air dryer, but the ventilation and heating system must be exchanged (steam-fans, steam-heater, etc.).

2. The excess steam must be condensed out by spate condenser. This condenser will substitute air filtration or air handling units. Depending on the existing air units it might be even more cost effective to install a condenser.

[5] Siegfried Schmidt, 2019, Potential and challenges for energy recovery from industrial drying system, HeatUp Workshop on high temperature heat pumps, 12.11.2016, Trondheim, Norway.

3. The insulation of the dryer should be increased since the drying temperature in SHS is normally higher than in air drying. The insulation must be sufficient to ensure that no cold bridges cause condensation in the system.

4. The construction of the dryer should ensure that as little as possible air or oxygen is present in the system in order to ensure an efficient drying process and to avoid air pockets in the system.

5. The dryer should be operated at atmospheric pressure in order avoid expensive pressurized drying chambers and product lock/valves.

3.4 Summary

SHS drying has a moderate energy saving potential of up to 20-30% when substituting thermal processes which are based on air, due to the higher heat transfer characteristics of steam. Such a substitution will however require product or case specific alteration of drying processes and system. The highest energy saving potential is in combination with mechanical vapor recompression.

4 Heat pump drying

The energy saving potential for heat pump assisted drying (HPD) is large and the Handbook of Industrial Drying states a drying efficiency of 95% for HPD compared to 35-40% for hot air drying.[6] However, industrial systems mostly operate at drying temperatures below 30°C (low temperature drying). These findings are consistent with the review article of Colak and Hepbasli[7]. Recent developments towards heat pumps operating at higher temperatures than commonly available will make it possible to utilize the potential of heat pump drying also for drying processes at higher temperatures.

4.1 Concept of heat pump drying

Modern industrial drying processes are either an open loop system using heated ambient air or closed loops system with recirculation of the drying air. Heat pumps are characterized by the possibility to utilize heat sources at low temperatures (at the evaporator) and supply heat sinks at a higher temperatures (condenser). For the case of closed loop drying this combined heat and cool load is used for the recovery of drying energy (basically the latent heat of evaporation of water) and deliver this energy back into the drying process in the form of de-humidified and re-heated drying air (see Figure 5).

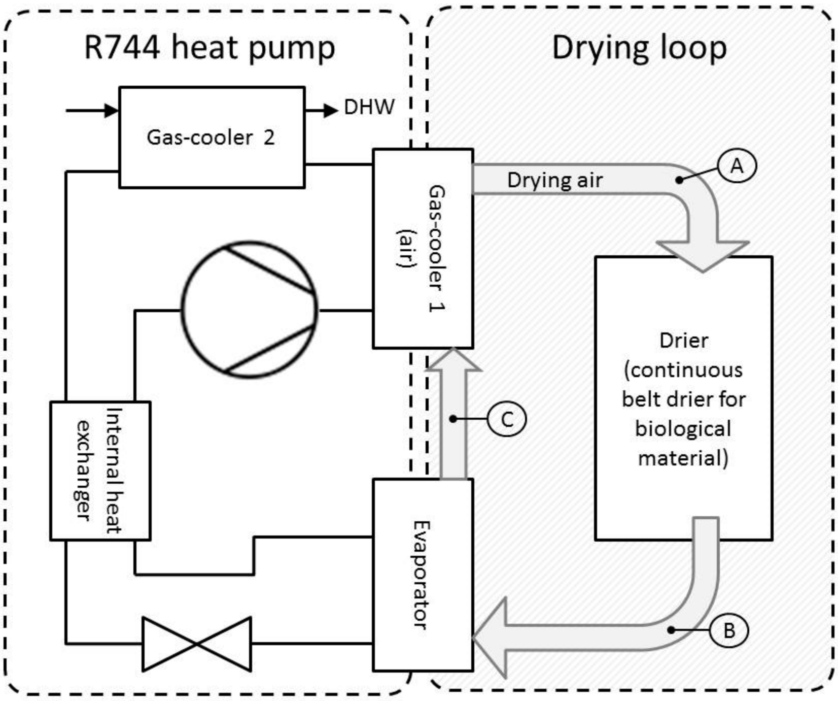


Figure 5: Main components of the simulated heat pump drying process with R744.

Heat pump drying consists of two loops: one loop for the drying air and one refrigeration cycle. At the evaporator of the heat pump, the drying air is cooled down below the dew point and the moisture from the air is condensed at the surface of the heat exchanger. Energy is hereby transferred to the refrigerant, which is evaporated. The evaporated refrigerant is then compressed and can now be condensed in the condenser at higher temperature. Hereby the formally transferred energy is given back to the drying air which is then re-

[6] Kiang, C. S. and C. K. Jon (2006). Heat pump drying systems. Handbook of Industrial Drying. A. S. Mujumdar. Boca Raton, FL, CRC Press. 3rd editio

[7] Colak, N. and A. Hepbasli (2009a). "A review of heat pump drying: Part 1 - Systems, models and studies." Energy Conversion and Management 50(9): 2180-2186

heated to its initial desired condition. It is necessary to install a second, external condenser in order to transfer the excess heat out of the system. The main source for the excess energy is the compressor, which also should be equipped with a rotation speed control in order to ensure optimum working conditions at varying heat and cooling loads. It is also recommended to install a bypass valve for the drying air, so that only the necessary amount of drying air is cooled and re-heated; this makes the operation more efficient[8].

The principle can be also used for open loop drying systems when the ambient air is heated to the initial drying temperature with help of the excess heat from the cold and humid drying air which is exhausted form the drying chamber. However heat pump assisted drying for open drying loops have no possibility to control the humidity of the drying air and most systems are therefore based on closed loop drying.

4.2 Example of potential for heat pump drying with R744[9]

HPD requires that the drying air is re-heated after de-humidifying to its initial drying temperature. This involves a significant temperature glide and sub-critical refrigerants will result in high heat transfer losses due to their stable condensation temperature as soon as condensing temperature should be a few Kelvins higher than the temperature of the outlet air. This could be avoided by using a working fluid in a trans-critical state, which rejects heat at gliding temperature. The thermodynamic properties of R744 seem to be a suitable refrigerant for heat pump drying, especially for drying processes between 30°C and up to 70°C. Being a natural refrigerant, R744 has per definition a Global Warming Potential of 1 and Ozone Depletion Potential of 0; hence its environmental impact is negligible compare to commercially available HFOs.

A continuously operated air dyer was simulated for drying temperatures of 45 °C, 60 °C and 70 °C and the energy recovery based on the described heat pump application was modelled according to Figure 5. Commonly these driers in general have specific energy consumptions between 0.8 and 2 kWh/kg. Table 3 shows the simulation results and the specific energy consumption can be reduced to below 0.3 kWh/kg. This is a significant energy saving potential which is currently not utilized by the industry.

Figure 6 and Figure 7 show the process in the temperature – entropy diagram and Mollier diagram, respectively. Since the drying temperature is higher than the critical point it is necessary to cool the refrigerant further down. In the present cases this was achieved by pre-heating DHW (domestic hot water), but also other heat sinks are possible to consider. The diagram shows also the corresponding cooling and re-heating of the drying air. It must be noticed that the necessary dehumidification of the drying air is achieved in the evaporator of the heat pump, which must be designed to handle and remove water condensate.

[8] Petrova, I., M. Bantle and T. Eikevik (2015). "Manufacture of dry-cured ham: A review. Part 2. Drying kinetics, modeling and equipment." European food research and technology: 1-12
[9] This chapter is based on a conference paper: Bantle, M., et al. (2016). Performance simulation on a heat pump drying system using R744 as refrigerant. 12th IIR Gustav Lorentzen Conference on Natural Refrigerants GL2016 : Proceedings, International Institute of Refrigeration.

Table 3: Energy flows, efficiencies and operational conditions for R744 heat pump assisted drier at 45 °C, 60 °C and 70 °C

Drying temperature:	45°C	60°C	70°C
Heat flow in evaporator	101 kW	109 kW	**118 kW**
Heat flow in gas cooler	100 kW	108 kW	**116 kW**
Compressor power	23 kW	28 kW	**32 kW**
COP[10] for heating	**4.3**	**3.9**	**3.6**
COP for heating and cooling	8.8	7.8	**7.2**
SEC[11]	968 kJ/kg	917 kJ/kg	**865 kJ/kg**
SEC	**0.269 kWh/kg**	**0.255 kWh/kg**	**0.240 kWh/kg**
High pressure	75 bar	100 bar	**130 bar**
Low pressure	37.9 bar	45 bar	**57.3 bar**
Mass flow of CO_2	0.56 kg/s	0.62 kg/s	**0.72 kg/s**
Moisture content air into drier	0.012 kg/kg	0.025 kg/kg	**0.039 kg/kg**
Moisture content air from drier chamber	0.018 kg/kg	0.033 kg/kg	**0.049 kg/kg**
Air temperature after condensation	17.1 °C	30.5 °C	**39.4 °C**
Air temperature from drying chamber	28.8 °C	39.2 °C	**46.4 °C**
Removed water	**0.024 kg/s**	**0.031 kg/s**	**0.037 kg/s**
Temperature after compressor	73 °C	87 °C	**96 °C**
Temperature before throttling	**24.5 °C**	**27.0 °C**	**30.2 °C**

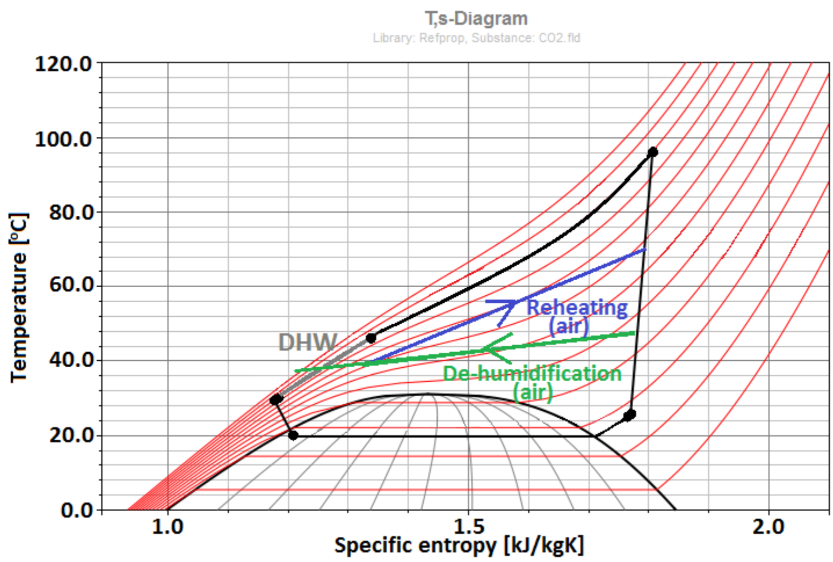


Figure 6: Heat pump assisted drier with R744 for drying temperature of 70°C

[10] *Coefficient of Performance*
[11] *Specific Energy Consumption*

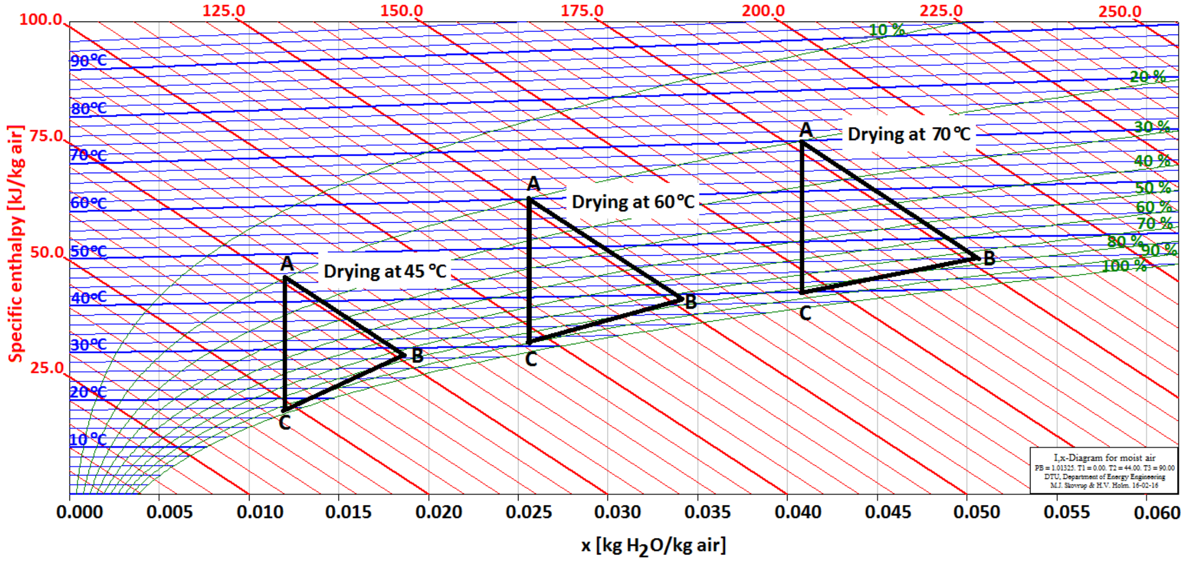


Figure 7 Mollier-diagram for the drying process at the different temperatures, where A denotes the inlet to the drying chamber, B the outlet and C the state after vapour condensation before reheating. For drying at 70 °C these states were at point A: 20 % relative humidity and 70 °C; point B: 75 % relative humidity and 46.4 °C and point C: nearly saturated at 39.4 °C

4.3 Discussion of heat pump drying

The performed investigation showed that a heat pump assisted drying process would need between 0.24 and 0.27 kWh/kg, depending on the drying temperature. Thus compared to the latent heat of water, the energy savings would be about 60 %. For an actual open type drying process, which uses and regards re-heated ambient air, the specific energy consumption is normally at least 0.8 kWh/kg, but can be even as high as 2 kWh/kg. However, it is difficult to compare these drying systems strictly on energy evaluations, since aspects like humidity control (which is possible with heat pump drying) are difficult to include in open type drying systems. In laboratory experiments, savings of 65 % were obtained if using a Dorin compressor in a CO2 cycle[12]. Most of the reported energy savings for heat pump assisted drying were between 30 and 50 %, based on different refrigerants. The highest reported result was a 60-80 % improvement.[13]

Introducing a heat pump seems possible at all the three temperatures considered, and would result in similar or slightly better energy savings as reported in different studies over the last years.

Closed loop drying requires controlled cooling, dehumidification and re-heating of the drying air and these processes result naturally in temperature glides. Since the R744 cycle operates in the trans-critical state the heat exchange losses for re-heating will be smaller compared to a heat pump cycle with constant condensation temperature. The choice of a trans-critical process also results in appropriate temperature differences in the heating process, and thus gives the ability to reduce exergy losses. The temperature glide for the air during cooling is smaller and it is more important to obtain a corresponding temperature glide for the heating process. The thermal properties of R744 in the trans-critical state are advantageous for the concept of heat pump assisted drying in general.

[12] Klöcker, K., E. L. Schmidt and F. Steimle (2002). "A drying heat pump using carbon dioxide as working fluid." Drying Technology 20(8): 1659-1671
[13] Strømmen, I., T. Eikevik, O. Alves-Filho, K. Syverud and O. Jonassen (2002). "Low temperature drying with heat pumps new generations of high quality dried products." Proceedings 2nd Nordic Drying Conference, Copenhagen Denmark, June 25th – 27th Ebook: ISBN 82-594-2550-5

Heat pumps which use mixtures (e.g. ammonia – water hybrid heat pumps[14]) have temperature glides at the heat sink and heat sources. Hence, they seemed even better suited for the application in heat pump drying.

With increasing drying temperature, the COP of the heat pump decreased and the net energy use increased. The process efficiency of the heat pump assisted drying was at the same time increased since the amount of removed water was higher at higher drying temperatures. This effect compensated for the reduced COP at higher drying temperatures.

Closed heat pump assisted drying loops always give a surplus of heat (primarily from the compression work), and thus an additional heat sink is necessary for this case, since the heat flow for cooling and re-heating of the drying air are equally large. The second gas-cooler (or condenser when using other refrigerants) gives the possibility to control the drying conditions continuously, resulting in stable drying temperatures and humidity. Systems which do not have this second gas-cooler (or condenser) are quite often operated in on/off regulation, when the drying temperature is getting to high.

The investigated heat pump system was based on a drier capacity which allows removing around 100 kg water per hour, depending on drying temperature and condition. The capacity of industrial driers can range from a few kilograms up to several tons of removed water per hour; so it is difficult to conclude on a general applicable drier size. The investigated system can be up- or downscaled to different drier sizes without influencing the process efficiency under the pre-condition that the size of the components of the heat pump can be adapted. The size and efficiency of the compressor are hereby the most limiting factors. With currently available compression technology it should be possible to upscale the system to a drier capacity of 500 kg/hour.

Further design evaluations should also include the possibility for cleaning of e.g. heat exchanger for reasons of sanitation especially in the food industry. Quite often, when drying biological material the air will be polluted with particles etc. which can agglomerate in the heat exchanger. Hence, cleaning must be also a design aspect for reducing thermal resistance and sustaining high heat transfer in the heat exchangers.
The present study did not investigate investment cost or return of investment and solely focused on the energy saving potential. Based on the performed analysis it will be possible to calculate these numbers for specific drying processes and products.

The energy saving potential of heat pump assisted drying was clearly identified and the dependency on the drying temperature (not the COP of the heat pump) is important for the energy saving potential.

[14] http://www.hybridenergy.no/

4.4 Mechanical Vapour Recompression

Mechanical Vapour Recompression (MVR) is a special heat pump application in which steam (R718) is used as refrigerant. The evaporation of the refrigerant unlike conventional heat pumps not done in a heat exchanger; instead the refrigerant is evaporated by the primary process, e.g. distillation or drying. In the literature MVR is sometimes referred to as open loop or open heat pump. One obvious advantage is that the main thermal process can act as an evaporator for the heat pump, which reduces the amount of needed components (= investment costs) and the heat transfer losses (= increased system efficiency).

For thermal processes operating above 100°C, pressurized steam is often used as energy carrier. There are several reasons for this, but the main reasons are the good thermal properties as an energy carrier, as well as the fact that water is cheap, easy available and non-toxic, making water/steam a very practicable solution. A large amount of components are available for steam based processes by different suppliers.

The earlier investigated case of superheated steam drying showed the potential of such an application with respect to available excess heat, energy efficiency and specific energy consumption of the main process. In the analysed case, the energy consumption could be reduced from around 800 kWh per ton of dried out water to 200-250 kWh per ton; this is an energy saving potential of up to 75%. A principal sketch of such a system is given in Figure 8.

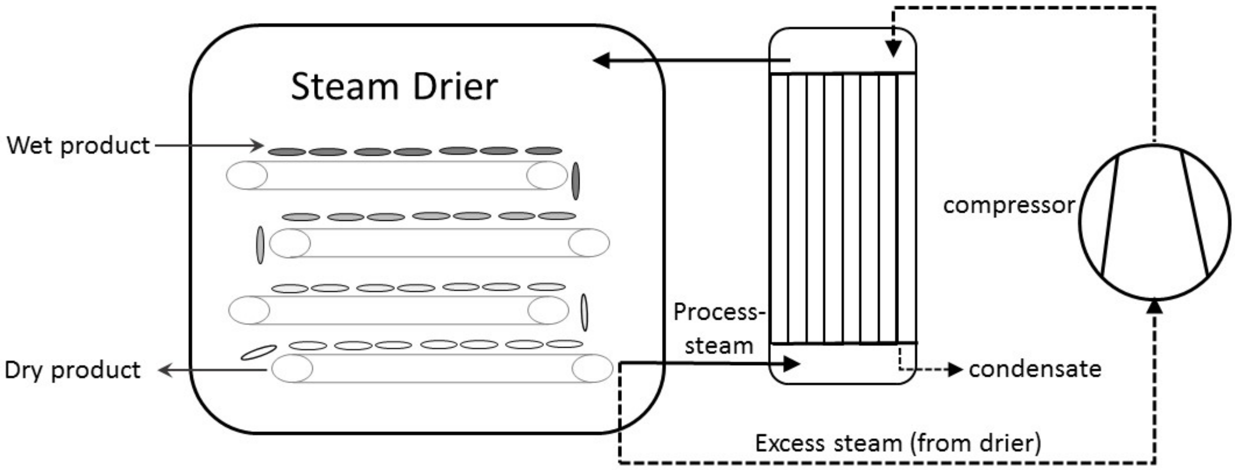
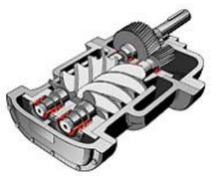
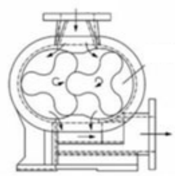


Figure 8 Schematic layout for superheated steam drier with energy recovery through mechanical vapour recompression.

It was investigated what kind of compression technology that could be used for such a system solution for MVR-Superheated steam drying (see Table 4). MVR compressors are available for thermal capacities above 5 MW at a high technological readiness level and depending on the required pressure ratio different technologies can be implemented. However, for small thermal capacities with relative high required pressure ratios (>4) there is a lack of energy and cost-effective technology.

Table 4: Possible compression technologies for MVR or steam based heat pumps.

Type	Compressor	Turbocompressor	Centrifugal Fan	Roots Air Blower
Pressure Ratio (single stage)	< 5	< 2	≤ 1.3	≤ 1.5
Temperature Rise	Single stage max. 40°C	Single Stage max. 20℃	Single Stage max.7℃	Single Stage max.~10℃
Max. Flow Rate	120 t/h	100 t/h	120 t/h	3-5 t/h
Impeller Type	Screw or piston compressor	Three-dimensional flow, centrifugal type	Two-dimensional flow, centrifugal type	Two-impeller or three-impeller, volume type
Impeller Material	Stainless steel	Stainless steel or titanium steel	Stainless steel	Cast iron, nickel plating or nickel-phosphorus
Manufacturing cost	High	Medium	Low	Quite low
Photos				
Realization of rotary speed	Direct or gear drive	Gear increase	Direct Connection with high-speed motor	Synchronous gear
Range of rotary speed	Commonly less than 4000 r/min	5000~40000r/min	Commonly less than 4000 r/min	150~3000r/min
Thin oil lubricating system	Yes, oil separator necessary	Yes, but not in contact with steam at all	No	Gear oil and grease lubrication, contacted with medium
Service life	Five years	Three years	Three years	Nearly one year

Around 85% of industrial dryers uses air as drying agent. In order to utilize the potential of superheated steam in drying application and MVR energy saving potential it is therefore necessary to substitute air with steam (see chapter 3). This will most likely require case specific R&D in order to establish a suitable dryer system before the MVR can be implemented. The chance for implementation of the technology is therefore highest for green field installations.

5 Pulse Combustion Drying

Pulse Combustion Drying (PCD) can be classified as a novel dehydration technology and is based on thermoacoustic pulse. This pulse is achieved by combustion of a fuel gas and the resulting acoustic shock wave is used to atomize the product. The drying rate is less than one second and evaporating water creates a sort of superheated steam atmosphere in the drying chamber. The principle of PCD is illustrated in Figure 9 and Figure 10.

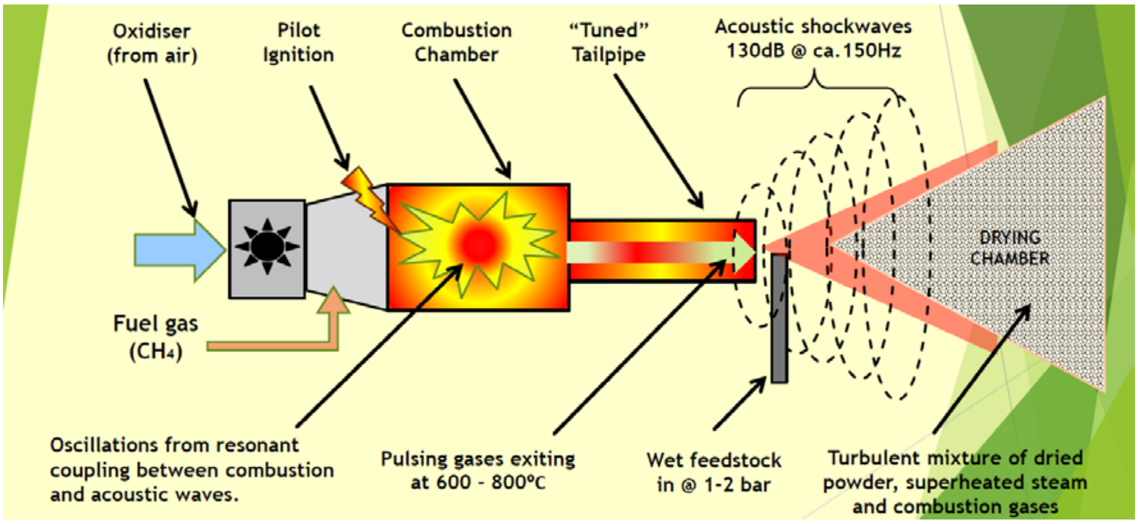


Figure 9: Working principle of the thermoacoustic Pulse Generator[15]

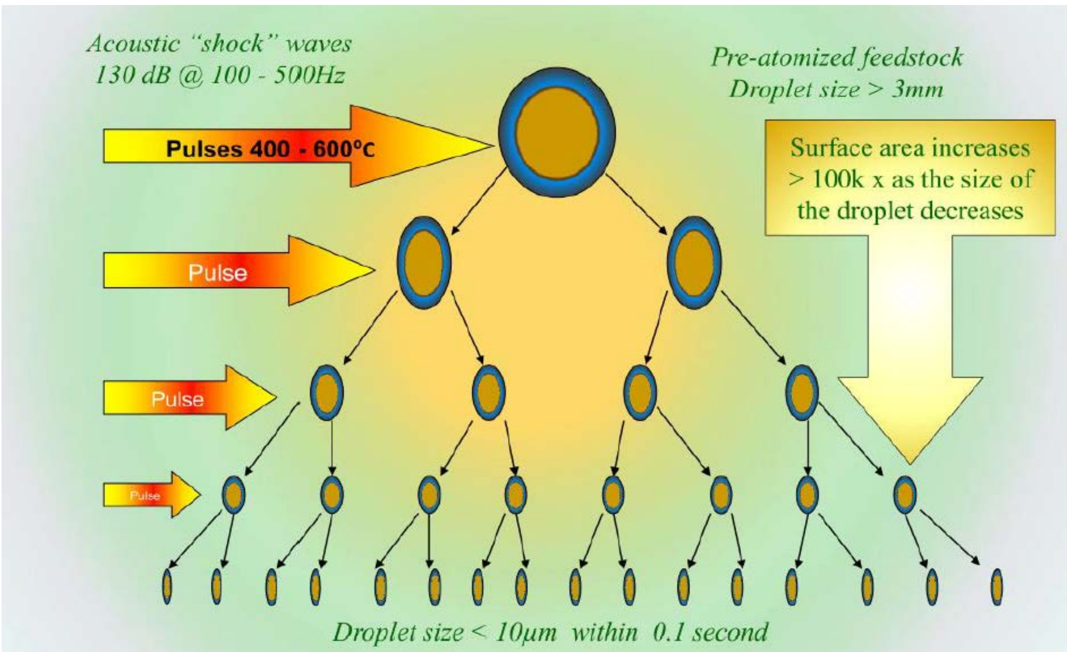


Figure 10: Atomization of the product in the acoustic shock wave [13]**.**

PCD appears to be a directly fired spray drying system, which is at least partially operated in an inert superheated steam atmosphere. The main potential of the technology is as follows:

[15] Oliver Hart (2017), Pulse Combustion Drying with Superheated Steam, Nordic Baltic Drying Conference, 7th to 9th June 2017, Hamburg, Germany. ISBN 978-82-92739-11-2

1. The specific energy consumption of the process can be as low as 1.1 kWh/kg evaporated water. Conventional spray dryers have commonly energy consumption between 1.6 to 2 kWh/kg and the **energy saving potential is therefore between 25 – 45 %.**

2. The **fast drying process** in an inert atmosphere can potentially give an increased product quality and no heat build-up in the product. However, the direct fired gas system might result in combustion residues in the final product.

3. The dryer can be designed in a way that can dry products with an initial moisture content between 60 – 98 % (dry base) The product must be a viscous slurry or paste and may require pre-processing. Field tests have shown that PCD can be used to dry hydrolysates as well as whole fish products and by-products. Hence the dryer could be used to utilize waste products which are currently discarded from the production chain (→ higher yield).

Some examples of dried food/feed products are shown in Table 5.

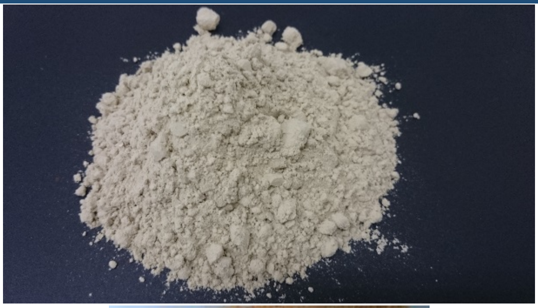
Limitations for PCD:

1. PCD is a relative new technology and has not many industrial references (less than 50 plants).
2. The technology has a high noise level and requires additional insulation.
3. The dried product is a fine or ultrafine product and the particle size distribution makes it difficult to handle.
4. The process is a direct fuel driven thermal dryer and will result in climate gas emissions.
5. Case specific product validation is necessary especially for food products.

Remark:

The technology "Pulse Combustion Drying" is based on information from a single supplier and the technological readiness level is not identified. The information received is quite generic and is not verified in own experiments. Future evaluation of this technology should therefore verify the potential and confirm especially the energy saving potential.

Table 5: Examples of dried material before and after pulse combustion drying.

Product	Raw material	Pulse Combustion Dried
Fish trimmings		
Tomato skin		
Fish (whole)		
Hydrolysate	n.a.	

6 Summary

"Drying" is a widely used, energy intensive process, but it is difficult to evaluate generic efficiencies measures. This must be done case or system specific. The present report is summarizing possible measures to increase energy efficiency in drying processes which can in principle be applied for all kinds of dryer and products. The technical descriptions of the suggested solution are not detailed and the aim was to give a general overview about different possibilities. For each suggested solution, a feasibility study is necessary to investigate case specific potential in cooperation with industrial partners.

The suggested measures can be summarized as follows:

1. Around 85% of all industrial dryers are based on air as drying agent. By replacing air with superheated steam an energy saving potential of 20-30% is possible. However, this also means that the drying system must be redesigned accordingly. The increased heat transfer properties of superheated steam could also be useful in other thermal process were air is currently used as heat carrier.

2. Pulse combustion drying as identified as possible replacement technologies for industrial spray dryers in order to increase the energy efficiency between 20% and 45% respectively. The potential was not verified by own experimental investigations, however the technology seems promising in the sense that is a fast drying process that can dry highly viscous products. On the other hand, it must be discussed if a direct fired gas dryer is a sustainable process with respect to future climate goals.

3. Recovery of excess energy through heat pump drying or mechanical vapour recompression has the highest potential and can save between 50% – 75% primary energy consumption in drying processes. The concept is well known and industrially implemented for low temperature drying (<30°C). The R&D challenge is to design suitable heat pump drying systems for high drying temperatures.

The suggested technologies for increased energy efficiency can in general be implemented in a drying temperature area from 20°C up to 150-200°C. This is the processing range of biological material which can mostly be found in the food industry and to a certain extend in the wood, paper and chemical industry.