Thin Film Drying Processes

'Energy- and economic aspects compared to spray drying'

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Abstract

This report gives a systematic comparison of the energy consumption and the investment- and energy costs for a conventional spray dryer in comparison to three conductive thin film drying processes. The evaluated thin film drying processes are: vacuum drum drying, agitated thin film drying and refractance window drying. The comparison is carried out for a drying capacity of 500 kg water/h by evaporation.

Taken all boundary conditions into account, it is concluded that for the evaluated conductive thin film drying processes a reduction in primary energy (15% to 35%), capital costs (45% to 65%) and operational costs (37% to 50%) can be expected.

Contents

Summary

Within the framework of the ISPT project 'Mild thin film drying', a techno-economic assessment is carried out. The objective of this assessment is to provide food industry with more evidence and guidelines concerning the energy use and economic aspects of conductive thin film drying technologies compared to convective spray drying technology. This assessment can be used to support food industry to switch to the more energy efficient thin film drying methods.

The thin film drying technologies within the scope of this study are: vacuum drum drying, refractance window drying, and agitated thin film drying. The working principle, process conditions, and capital and operational expenditures are investigated for both thin film drying technologies and spray drying technology through a literature study. Based on this a comparison is made between the different drying processes.

In addition, a generic calculation model is used to calculate the primary energy consumption of the mentioned drying processes. As input, the process conditions for the spray drying process are defined by an industrial end-user and for the thin film drying processes by the project partners. The calculation is carried out for an evaporation capacity of 500 kg water per hour. Capital costs (CAPEX) for the spray dryer were obtained from an industrial end-user and are quoted or calculated for the thin film dryers. The operational costs (OPEX) are based on the energy and maintenance costs.

Results show that in comparison to the spray drying process a primary energy reduction in the range of 15% to 30% can be expected for the evaluated thin film drying processes. A reduction in CAPEX of 45% to 65% can be expected for the mentioned drying capacity of 500 kg/h for the evaluated thin film dryers, which is mainly a result of redundant feed and atomization, intake air heating and exhaust air handling equipment compared to spray drying. Regarding the operational costs (OPEX) a reduction of 37% to 50% can be expected for the evaluated thin film drying processes.

This analysis holds for the present situation with respect to the electricity system and energy prices. Future changes in this situation will require a reassessment.

1

Background

Drying and dewatering is an important step in the process industry, using around 18% of the annual process heat demand in Dutch industry (510 PJ). Food industry is one of the major end-users. Drying of liquid solutions and suspensions for food industry is achieved by various drying technologies. Generally two types of methods are used, i.e. so called convection and conduction drying methods. During convection drying, for example spray drying, there is physical contact between the heating medium (usually air) and the product to be dried. For conduction drying, for example drum drying, the energy for evaporation is supplied by a secondary medium via heat transfer through a wall.

When applying conductive drying the product to be dried should not be exposed at too high temperatures for a too long period of time. Therefore, the product to be dried is applied as a thin film on the drying machine which minimizes drying times. Lower drying temperatures can be achieved by applying a vacuum, resulting in better product quality.

Because of their relatively mild drying conditions, conductive mild thin film drying technologies are often referred to as promising alternatives to conventional spray drying technology. In terms of energy efficiency it is stated that the convective spray drying process is less energy efficient compared to conductive mild thin film drying processes. To enable food industry to switch to the more energy efficient thin film drying methods, more evidence and guidelines should be provided. The objective of this study is to provide such evidence and guidelines, by carrying out a systematic comparison of the energy- and economic aspects of conductive thin film drying technologies compared to spray drying technology.

2

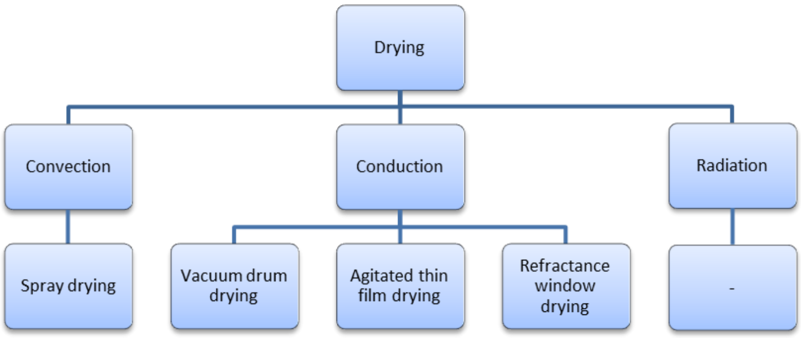
Drying technologies

In general drying technologies can be distinguished into convection, conduction and radiation drying methods. This report focusses on three different conductive thin film drying technologies compared to one convective drying technology, i.e. spray drying, which is the benchmark technology. The reviewed thin film drying technologies are:

- Rotating vacuum drum drying
- Agitated thin film drying
- Refractance window drying.

An overview of the scope of drying technologies within this report is given in **Figure 1**.

Figure 1: Scope of drying techniques



2.1 Benchmark technology

2.1.1 Spray drying

The spray drying process (see **Figure 2**) is a widely used particle formation process by which aqueous or organic solutions, emulsions and suspensions can be converted into a dry powder with a relatively narrow particle size distribution. Thanks to short contact times, spray drying is well suited even for heat-sensitive materials (e.g. enzymes, medicines). The physical properties of the resulting product (such as particle size and shape, moisture content, and flow properties) can be controlled through the selection of equipment (type of nozzle) and the manipulation of process variables (such as gas and liquid flow rates, atomising gas pressure or inlet temperature). A key step in spray drying is the atomization of the feed liquid into fine droplets through which the current of hot air is passed. This can be achieved by a range of nozzle types, such as rotary- or pressurized nozzle. Atomization creates a very large surface area for the heat and mass transfer. Hence drying is very fast. The hot air coming in contact with the droplets increases its temperature up to around *wet bulb temperature* of air. The product/air flow in the drying chamber can be co-current, counter current or even mixed flow. A summary of the advantages and disadvantages of spray drying can be find in **Table 1**.

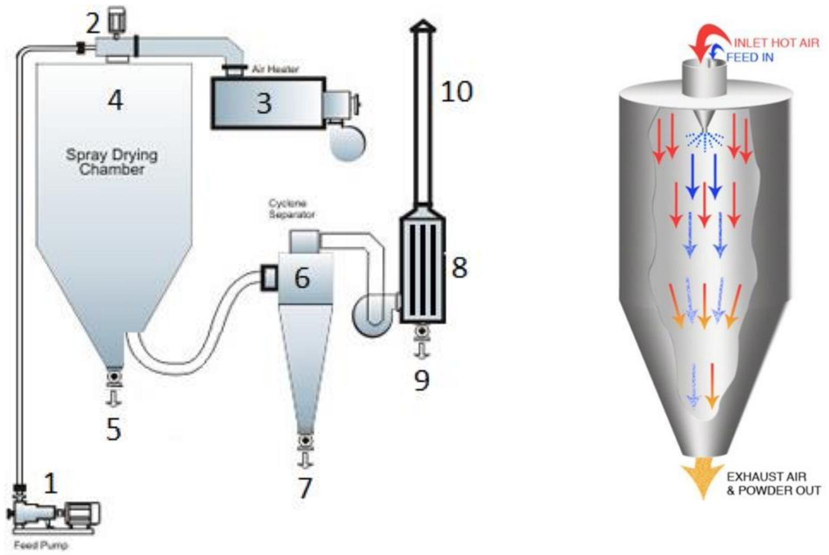
Table 1: Summary of advantages and disadvantages of spray drying [1]

Advantages	Disadvantages
Permits high-tonnage production in continuous operation with relatively simple equipment	Highly energy intensive, but use of multiple drying stages can allow for recycling of heat
Product properties and quality are effectively controlled	High initial investment compared to other types of continuous dryers
High heat-transfer coefficients at high temperature differences	Product recovery and dust collection increase the cost of drying
Easy to descale	Poor heat transfer at low temperature differences or with viscous liquids
Nozzles and atomizers are easily plugged	Inability to produce high-bulk density product

Process description

The liquid feed is pumped (1) to the atomizer (2), where it is dispersed into discrete droplets, by using hot air coming from the air heater (3). The droplets enter the hot air drying chamber (4) at high speed to create dry particles. The larger particles, which is the main powder fraction, exits the drying chamber through a rotary valve (5).

Figure 2: Illustration of co-current spray drying process and drying chamber [source; Unitop, EST]



Air, exiting the drying chamber, that is mixed with finer particles enters the cyclone (6) which then allows this fine powder fraction to exit through a rotary valve (7). The process air is filtered in a baghouse filter (8) to collect ultra-fines (9), so that only clean air is released to the environment (10).

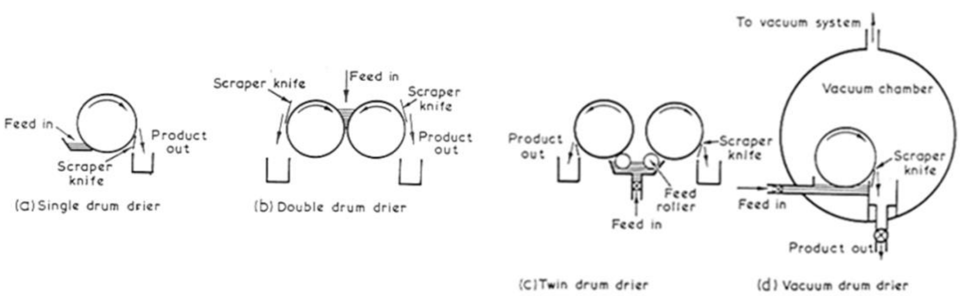
Process conditions
The resulting rapid evaporation maintains a low droplet temperature corresponding to the wet bulb temperature of the air so that high drying air temperatures (up to 270°C, as in drying of instant coffee) can be applied without significantly affecting the product. The droplet drying time is very short. This combination of short drying time and low product temperature (90-110°C) allows the spray drying of heat-sensitive products at atmospheric pressure [9].

2.2 Thin film drying technologies

2.2.1 Rotating drum drying

Rotating drum dryers, also known simply as drum dryers, dry material on the surface of a heated, rotating drum. The liquid feed of a drum dryer is applied onto one or more slowly rotating, internally (steam) heated drums. The diameter of typical drums ranges from 0.5 m to 6 m and the length from 1 m to 6 m. The dried product is removed from the drum by a static scraper. Drum dryers are primarily used to dry slurries and pastes. They are available in several types; single drum, double drum, twin drum and vacuum drum (see **Figure 3**). Selection is based on production rate, heat transfer and system design [1]. High temperatures in drum drying remain a concern because of severe quality loss in heat-sensitive products. For materials sensitive to heat damage, a vacuum drum dryer may be used to reduce drying temperature. This also solves problems originating from atmospheric contamination and climatic conditions, which lead to uniform operating results. This versatility of design allows for the use of rotating drum dryers in a wide variety of industries, ranging from food to chemical.

Figure 3: Conventional diagrams of several types of drum dryers [2]



Compared to spray drying, which can only process liquid feed, drum dryers can dry very viscous foods, such as pastes and gelatinized or cooked starch, which cannot be easily dried with other methods. The drying rate and energy efficiency is high. Limitation of drum drying is that the machines are big and bulky and the product feed should sustain thermal destruction, when no vacuum is used. A summary of the advantages and disadvantages of drum drying can be find in **Table 2**.

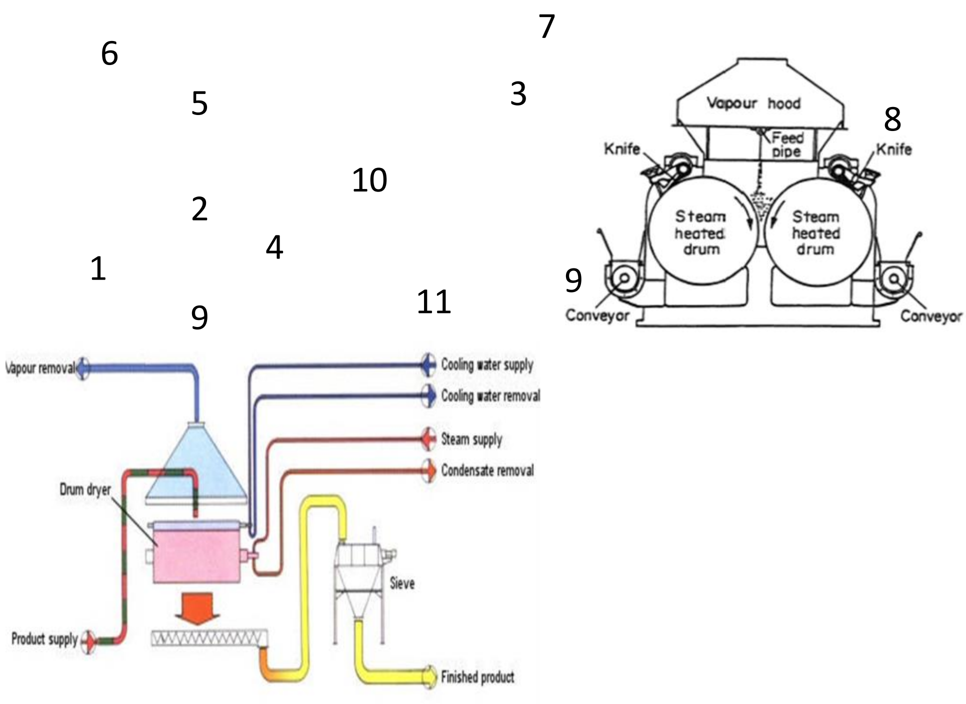
Table 2: Summary of advantages and disadvantages of rotating drum drying [1], [6]

Advantages	Disadvantages
One of the most energy efficient drying methods	Big and bulky, requires a large amount of space
Relatively low cost (except vacuum drum dryers)	Vacuum drum dryers are relatively expensive
Large variety of feed and product moistures possible	Relatively low throughput compared to spray drying
Large drying capacity	
Easy to operate and maintain	

Process description

The product feed is pumped (1) to the rotating drum dryer (2), where it is applied continuously as a thin film on the underside or top of the main drum. Steam is supplied (3) to the inside of the drum, where it condenses due to the heat uptake by the product through the wall of the drum. Condensate is continuously removed (4) from the drum. The water or solvent in the product feed evaporates and is collected in the vapour hood (5) before it is released to the atmosphere (6). The product dries on the outside of the rotating drum. The dried product can be cooled (7) to facilitate product removal. The dried product layer is removed by the static scraper knife (8), before transported by the conveyor belt (9) to a sieve (10) where the finished product (11) leaves the process.

Figure 4: Illustration of the drum drying process and with a double drum dryer [source: Andritz-Gouda]



Process conditions

Steam at temperatures up to 200°C heats the inner surface of the drum for atmospheric drum dryers. For vacuum drum dryers, low pressure steam or hot water of around 90°C

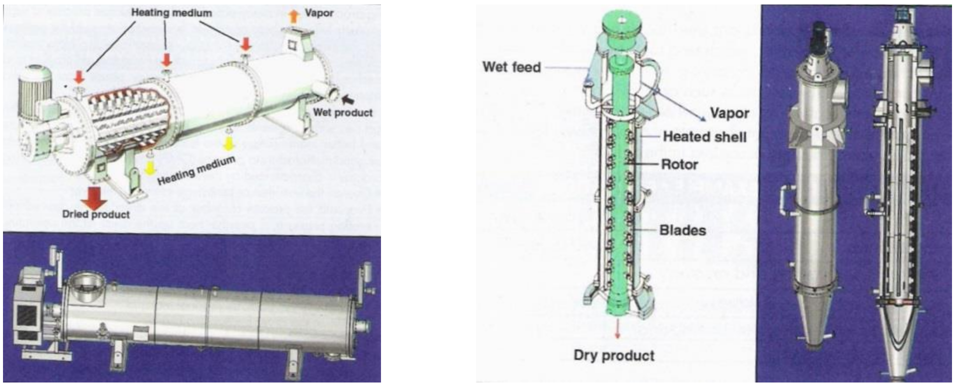
[11] is used. The moist material is uniformly applied in a thin layer (0.5 mm–2 mm) onto the outer drum surface. Product temperatures are usually in the range of 120-170°C for atmospheric drum dryers and between 35-60°C for vacuum drum dryers [11]. Most of the moisture is removed at water boiling temperature, which is at 100°C for atmospheric drum dryers, and is vacuum pressure depended for vacuum drum dryers. For instance, at 100 mbara the water boiling point is at 46°C. The residence time of the product on the drum ranges from a few seconds to dozens of seconds to reach final moisture contents of less than 5% (wet basis). In the operation of a drum dryer, a delicate balance needs to be established among feed rate, steam pressure, roll speed, and thickness of the product film. The energy consumption in an atmospheric drum dryer may range between 1.1 and 1.6 kg of steam per kg of evaporated water, corresponding to energy efficiencies of about 60%-90% [3], [4], [5], [8]. Under ideal conditions, evaporation capacities of an atmospheric drum dryer are typically between 10 to 80 kg $H_2O/hr.m^2$ [5]. A drum dryer can produce products at a rate between 5 kg $hr^{-1}m^{-2}$ and 50 kg $hr^{-1}m^{-2}$, depending upon type of foods, initial/final moisture content, and other operating conditions [3]. Andritz Gouda mentions a product capacity in the range of 10 $kg/hr/m^2$ for vacuum drum dryers [26]. Electrical drive power of (vacuum) drum dryers depends on the product and number of drums used and are reported to be in the range of 0.5 to 8 kW/m^2 drying surface [25].

2.2.2 Agitated thin film drying

Thin film or wiped film dryers are generally similar in operation to thin film evaporators and are suitable for drying solutions or suspensions containing typically no more than 60% solids. The product is a dry powder which usually has a mean size in the range of 200-600 µm. Agitated Thin Film Dryers (ATFD) have high heat transfer rates and consequent short drying times. The operating pressure in the drying chamber can range from near vacuum to atmospheric pressure [7].

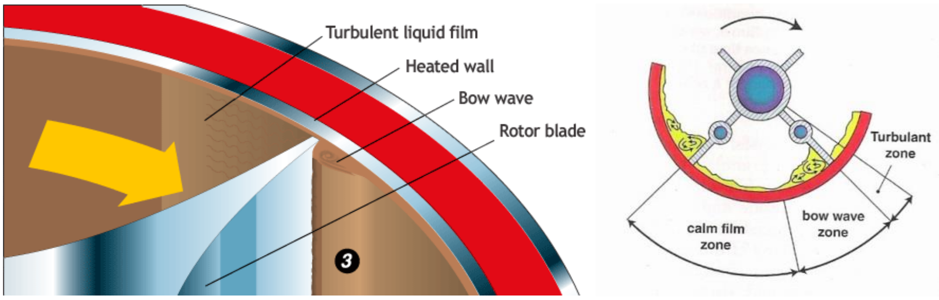
Basically, there are two type of ATFD: horizontal and vertical (see **Figure 5**). Choosing which one to use depends on the consistency of the feedstock, the volatile component contained in the feed stream, product behaviour, and desired form of the final product. Horizontal designs are ideal for applications where longer residence times are required for mass transfer and reactions, or where headroom is limited. An ATFD consists of a cylindrical body with a heating jacket and a rotor inside of the shell which is equipped with rows of pendulum blades all over the length of the dryer. The heating jacket is set at a certain temperature, predetermined by the feedstock, and is heated with steam, warm water, thermal oil or electrically [1].

Figure 5: Illustrations of a horizontal (left) and vertical (right) Agitated Thin Film Dryer [source: LLC]



The hinged blades spread the wet feed product in a thin film over the heated wall. The thickness of the layer is defined by the clearance between the blade and the wall. A highly agitated bow wave is formed in front of the rotor blades (see **Figure 6**).

Figure 6: Illustration of the pendulum rotor blade inside the shell with zone typology [source: LCI, SMS]



Continuous washing by the bow waves minimizes fouling of the thermal wall where the product or residue is concentrated most. The turbulence increases as the product passes through the clearance before entering a calming zone situated behind the blades (see **Figure 6**). The volatile component evaporates continuously. The product layer is typically less than a millimeter in thickness. The hinged pendulum blades are designed to give a minimum clearance with the dryer wall to prevent fouling of the heating surface by product, but do not themselves contact the heated wall. An overview of the advantages and disadvantages of spray drying can be find in **Table 3**.

Table 3: Summary of advantages and disadvantages of ATFD [1]

Advantages	Disadvantages
Low energy consumption	Not suitable for coarse feedstock
Compact design	Won't produce granular final products
Flexibility in operation	
Short residence time, single pass to dry material	
Low operation temperature	
Can handle many feedstock consistencies	
Continuous, fully enclosed processing	
High turbulence in product layer	
High heat-transfer rate	

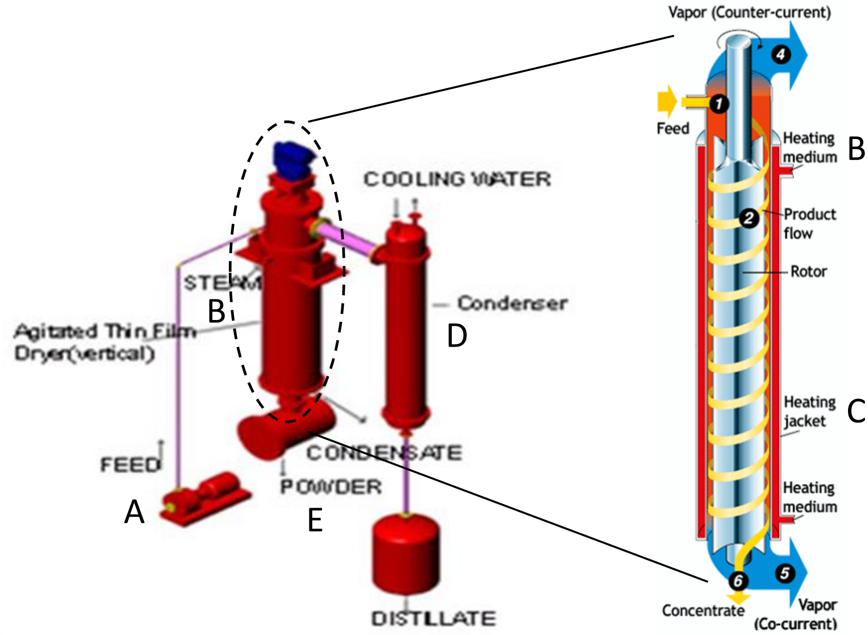
Advantages	Disadvantages
Low energy consumption	Not suitable for coarse feedstock
Low maintenance	

Process description

Product is pumped (A) from the feed tank to the ATFD and enters above the heated zone (1), where it is evenly distributed over the unit's inner surface by the rotor (see **Figure 7**). As the product spirals (2) down the wall, bow waves (3) developed by the rotor blades (see **Figure 6**) generate highly turbulent flow, resulting in optimized heat flux and mass transfer.

Volatile components are rapidly evaporated by heat coming from the steam supply (B) heating up the heating jacket (C). Vapours flow either counter-currently (4) or co-currently (5) through the unit, depending on the application. In both cases, exiting vapours are ready for condensing in a separate condenser (D) for solvent recovery or subsequent processing. Non-volatile components, i.e. the powdered product, are discharged at the outlet (E) which is at the bottom of the ATFD (6).

Figure 7: Illustration of process equipment and reactor of a vertical ATFD process [source: Unitop, LCI]



Process conditions

Unlike traditional agitated dryers, which operate at high temperatures, agitated thin film dryers operate at low pressures and low temperatures. By using low temperature heat the dryer has a lower retention time and the walls of the dryer do not foul, which is a common problem in some dryers [1]. Several suppliers claim operating pressures inside the evaporation chamber varying from 1 mbara up to 1 bara, meaning water evaporation temperatures from below 0°C up to 100°C. For one mentioned typical ATFD application (pharmaceutical/bulk drugs), steam of 3 barg is used as a heat source [12]. Heat operating temperatures of up to 300°C are reported, with evaporation areas from

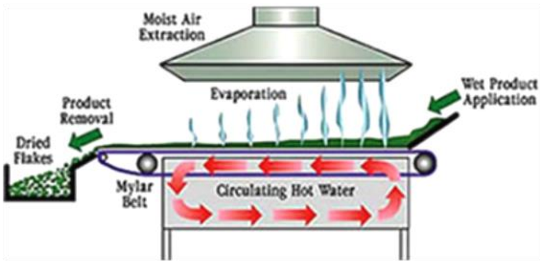
1 up to 50 m^2 [12], [13]. Moisture levels in the powdered product are claimed to be in the range from a few tenths of a percent up to 10-15%. As the solids content of the feed stream increases, temperature sensitivity and viscosity generally increase, creating the need for short residence time. Under ideal conditions, the evaporation capacity of an ATFD can be up to 30 kg H_2O/hr.m^2 [20]. Total electrical power consumption for one specific case with a total heat transfer area of 25 m^2 is reported to be 35 kWe [12], resulting in an electricity use of 1.4 kW/m^2 evaporation area.

2.2.3 Refractance window drying

Refractance Window drying™, developed by MCD Technologies[1], is a relatively new development that falls within the contact, indirect, or film-drying techniques, and has the most similarity to rotating drum drying. In Refractance Window (RW) drying systems thermal energy is transferred from hot water to liquid product feed material deposited as thin film on a plastic conveyor belt (see **Figure 8**). By doing so, liquid foods (purees, juices, suspensions, etc.) are converted into powders, flakes, or sheets.

[1]Refractance Window Drying is a Registered Trademark of MCD Technologies (www.mcdtechnologiesinc.com)

Figure 8: Illustration and picture of the Refractance Window drying process [MtCapra, Sednanatura]



In the RW system, the wet feed material is dried in relatively short times, typically 3-5 min, at atmospheric pressure [8]. The RW drying method has become attractive for applications in the food industry, especially because the dried products are claimed to be of high quality and the equipment is relatively inexpensive. Compared to freeze drying, the cost of RW drying equipment are claimed to be approximately one third to one half, while the energy costs are less than half [8]. An overview of the advantages and disadvantages of RW drying can be find in **Table 4**.

Table 4: Summary of advantages and disadvantages of RW drying [8], [10], [15]

Advantages	Disadvantages
Dried products are of high quality	Intended primarily to dry liquids
Equipment is relatively inexpensive	Modest throughput
Low energy consumption	Higher cost compared to drum and spray drying
Divers energy sources	
Short drying times (most products in 2-5 minutes)	
Atmospheric pressure	
Mechanical simplicity	

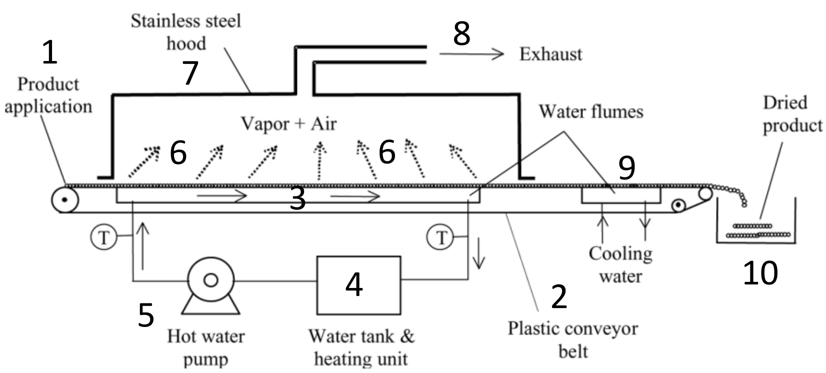
Process description

During the RW drying process (see **Figure 9**), wet raw material (1) is applied to the surface of the drying system's conveyor belt (2). The belt is a food grade Mylar belt floating on the surface of a heated cistern (3) containing circulating hot water coming from the heating unit (4) and pumped around by a hot water pump (5). The circulating hot water is heated either by direct steam injection or through a shell and tube heat exchanger [15]. Because the plastic sheet is very thin it almost immediately reaches the temperature of the circulating hot water.

The heat from the cistern's water is claimed to be transferred mainly by infrared radiation from the hot water by way of a "refractance window" through the Mylar belt, which bottom surface is in contact with hot water, to the water present in the raw material laying. However, *recent insights on the underlying thermodynamics of the process show that the main modus of heat transfer (99% of the heat flux) is conduction instead of infrared radiation* [14], [29].

As the product feed material travels down the conveyor belt, the water in the material evaporates (6). The moist air is captured with a stainless steel hood (7) and extracted from the process (8). At the end of the conveyor system, the dried product is cooled (9), to facilitate product removal, and collected (10).

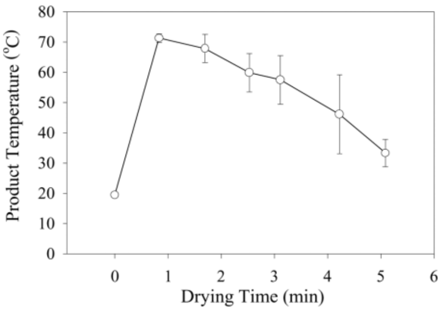
Figure 9: Illustration of RW drying process [8]



Process conditions

The RW drying system utilizes circulating water, usually at 95-98°C, at atmospheric pressure to transfer thermal energy to the material to be dried [8], [14], [15]. The heated water is recycled and reused, improving the thermal efficiency of the system. For most drying conditions the actual product temperature is usually below 70°C (due to the evaporative cooling and product detachment) for a period of three to five minutes [8], [15], as can be seen in **Figure 10**. For instance, the residence time for RW drying of pureed asparagus from about 98% to 4% moisture content (wet basis) is 4.5 minutes [15].

Figure 10: Typical temperature profile for puree of thickness 0.7-1.0 mm during RW drying on a moving belt with process water of 95°C [Abonyi et al.]



Under ideal conditions the reported evaporation capacity of an RW dryer can be up to 10 kg H_2O/hr.m^2 [8], [15] or even 16 kg H_2O/hr.m^2 [30]. For one specific case the total electrical power consumption for a heat transfer area of around 45 m^2 is reported to be 86 kW [30], resulting in an electricity use of 2 kW/m^2 evaporation area for this case.

2.3 Literature based comparison

When comparing thin film drying processes with spray drying, one has to keep in mind that these are two different kind of drying techniques with not only their own distinct heat transfer mechanism but also with difference in type of feedstock (like suspension, emulsion, % dry matter) and finished product. From this point of view it makes more sense to make a mutual comparison between thin film drying techniques, rather than a comparison to spray drying.

2.3.1 Typical process parameters

An overview of the drying capacity, product temperature and thermal efficiency of the different drying technologies within the scope of this study is given in **Table 5**. From these figures it can be seen that the reported thermal efficiency of the mentioned mild thin film drying technologies in literature is around 25-40% higher than spray drying.

Table 5: Theoretical comparison of spray dryer against different thin film drying technologies [8], [15]

Dryer type	Typical drying capacity [kg H_2O/h per m^3 or m^2]	Typical product temp [°C]	Thermal efficiency [%]
Spray dryer	1-30 m^{-3}	80-120	51-20
ATFD	-30 m^{-2} [20]	45-60 [22]	90- [23]
Drum dryer (for pastes)			
- Atmospheric	10-80 m^{-2}	120-130	78-35
- Vacuum	~10 m^{-2} [26]	35-60 [11]	?
RW-dryer			
- Pilot scale	6-10 m^{-2}	70-90	48-28
- Full scale	3.1-4.6 m^{-2}	90-95	77-52
- Dry-On-Water	1-10 m^{-2}	60-70	>90

It can also be seen that the maximum thermal efficiencies for the drum dryer and RW-dryer are comparable, whereas ATFD claims higher maximum efficiency. For comparison, direct heated conveyor dryers usually have lower efficiencies (20–40%) while their drying capacity is about 2-15 kg/m2.h [8]. Concerning RW-drying, ILVO (Instituut voor Landbouw- en Visserijonderzoek) claims to obtain higher thermal efficiencies (>90%) with their pilot scale RW drying technology (Dry-On-Water™) compared to the other mentioned RW-drying technology [16]. Recently ILVO and Spiessens signed a license agreement for commercialization of the Dry-On-Water technology [24].

2.3.2 CAPEX and OPEX

No exact data could be found In literature concerning capital and operational expenditures of the drying technologies under investigation. ILVO made a qualitative comparison of their Dry-On-Water technology compared to several competing technologies, including spray drying and drum drying, as can be seen in **Table 6**.

Table 6: Comparison of costs, (pre-)processing- and setup/clean up time of different dryers [17]

Cost factor	Dry-On-Water™	Spray drying	Drum drying
Equipment costs	Medium	Medium	Medium
Maintenance costs	Low	High	-
Energy costs	Low	Medium	Medium
Preprocessing	Low	High	Low
Processing time	Low	Low	Low
Setup/Cleanup time	Low	High	-

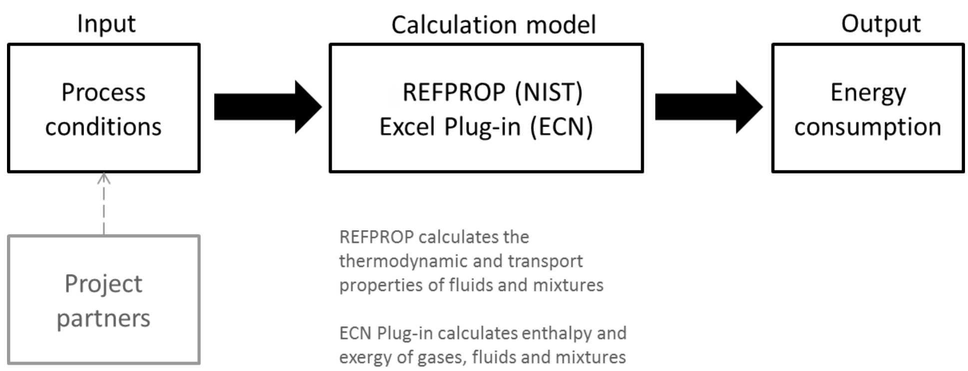
From this comparison it can be concluded that equipment costs for the mentioned technologies are claimed to be in the same order of magnitude, while the difference is in the operational costs.

3

Comparison of energy consumption

In this chapter the energy use and -efficiency of the thin film drying processes within the scope of this study are compared to the spray drying process as well as mutually. The process conditions are defined by the project partners and were used as an input for the calculation model (see **Figure 11**).

Figure 11: Schematic lay-out of the methodology used for calculating the primary energy consumption



3.1 Calculation model

To calculate the primary energy consumption a generic calculation model is used for all drying processes. An simplified representation of the calculation model can be seen in **Figure 12**. To make a comparison of the energy consumption between the different drying processes, the calculated primary energy use is expressed in primary energy use per ton water removed. By doing so, different drying processes with their own distinct process parameters and conditions (like % d.m. of feedstock and product, mass flow, etc.) can be compared.

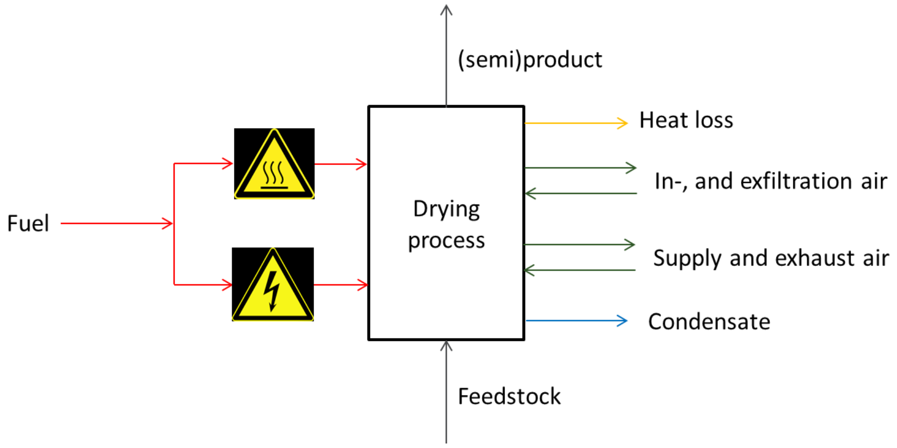
The primary energy use for all drying processes is based on the calculated specific (final) energy use, which is subdivided into:

- energy use for heating purposes (GJ/ton_{water} evaporated)
- energy use for auxiliary electricity use (kWh/ton_{water} evaporated)

In addition, the following efficiencies are used for the production of electricity and heat:

- Power plant: 45 %
- Hot water boiler: 95 %
- Steam boiler: 95 %
- Air heater: 85 %

Figure 12: Generic calculation model for reviewed drying processes



3.2 Boundary conditions

3.2.1 Spray drying

An overview of the process parameters and calculated energy use for the spray drying process can be found in the 'Benchmark report' [27]. This report also gives an overview of the process conditions, CAPEX and OPEX of the spray drying process. In the Benchmark report the feedstock is dried in a spray drying tower and a subsequent fluidized bed dryer. The energy use of the fluidized bed dryer (GJ/ton_{powder}) is very small compared to the energy use of the spray drying tower.

3.2.2 Thin film drying processes

An overview of the process parameters for the thin film drying processes can be found in **Table 7**. As can be seen, all thin film drying processes have a drying capacity of 500 kg H_2O/h and feedstock is dried from 20% dry matter (d.m.) to finished product of 90% d.m. The main difference in operating conditions between the thin film drying processes is due to the fact that vacuum drum drying and ATFD operate under vacuum pressure, whereas RW-drying operates at ambient pressure.

Table 7: Overview of the process parameters is input for the calculation model for the reviewed drying processes

	Vacuum drum drying	ATFD	Refractance Window drying
Drying capacity [kg H_2O/h] [1]	500	500	500
Process pressure [bara]	0.05[2]	0.05[4]	1[3]
Feedstock input [4]			
- temperature [°C]	20	20	20
- [% d.m.]	20	20	20
Product output [4]			
- temperature [°C]	60	60	60
- [% d.m.]	90	90	90
Drying surface [m2]	41 [5]	21 [5]	32[3]
Supply air [6]			
- temperature [°C]	-	-	25
- humidity [g H_2O /kg]	-	-	10
Infiltration air			
- mass [kg/h] [7]	0.25	0.25	-
- humidity [g H_2O /kg] [6]	10	10	-
- temperature [°C] [6]	25	25	-
Exhaust air [8]			
- temperature [°C]	-	-	27
- humidity [g H_2O /kg]	-	-	21
Exfiltration air [9]			
- humidity [g H_2O /kg]	33	33	-
Hot water/steam system [10]			
- pressure [bar]	2	2	1[8]
- supply temperature [°C]	120	120	95[8]
- return temperature [°C]	100	100	t.b.c.
Electric power			
- Total power [kW/m^2]	-	1.4[11]	1.3[3]
- Vacuum pump [kW]	t.b.c.	-	-
- Drive power [kW/m^2]	1.8[12]	-	-
- Pumps, fans [kW]	t.b.c.	-	-
- Conveyor belt [kW]	-	-	-
Heat loss [% of gas supply] [13]	5	5	5

[1] As discussed during progress meeting
[2] Andritz Gouda, vacuum drum dryer for continuous process (Menno Maingay)
[3] MCD Technologies – GW Dryer specifications
[4] As agreed on by project partners for setting boundary conditions
[5] Ter Horst & Chaabane, ATFD Case Study, Corbion Purac, ISPT, RUG, 2016
[6] Assumption, based on inside air temperature of building and relative humidity of 50%
[7] Assumption, infiltration caused by removal of dried product and leaking
[8] University of Idaho, 'Unique features of RW drying, assuming relative humidity of 90%
[9] As agreed on by project partners for setting boundary condition, RH =100%
[10] Assumption, based on LP-steam system
[11] KEP Engineering Services PVT.LTD, Agitated thin film dryer
[12] ANDRITZ Seperation, Gouda double drum dryer average drive power (41m2)
[13] Assumption, based on (small) scale of installation
t.b.c. = to be calculated

3.3 Energy efficiency

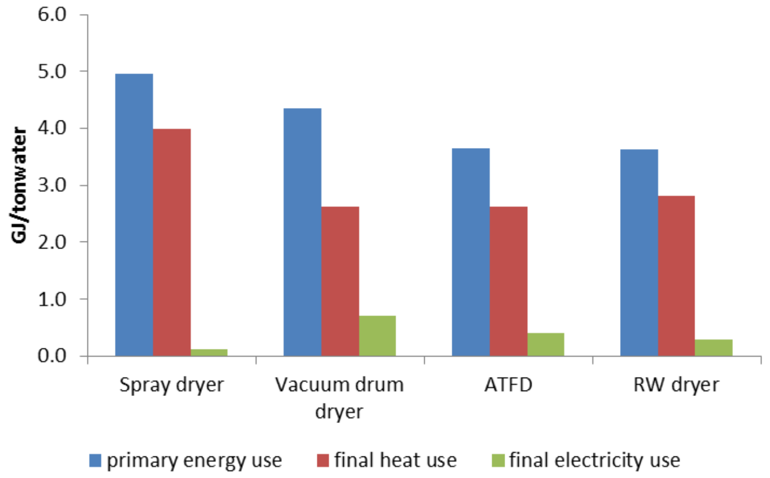
An overview of the key parameters for energy consumption of the spray drying process and the thin film drying processes can be found in **Table 8**. The detailed mass and energy balance can be found in Appendix A.

Table 8: Overview of the key parameters for energy consumption (results in energy/ton_ H_2O removed)

	Spray dryer	Vacuum drum dryer	ATFD	RW dryer
Final heat use [GJ/ton$_{water}$]	3.99	2.63	2.63	2.81
Final electricity use				
- [kWh/ton$_{water}$]	33.5	199.0	111.3	82.5
- [GJ/ton$_{water}$]	0.12	0.72	0.40	0.30
Primary energy use [GJ/ton$_{water}$]	5.0	4.4	3.7	3.6

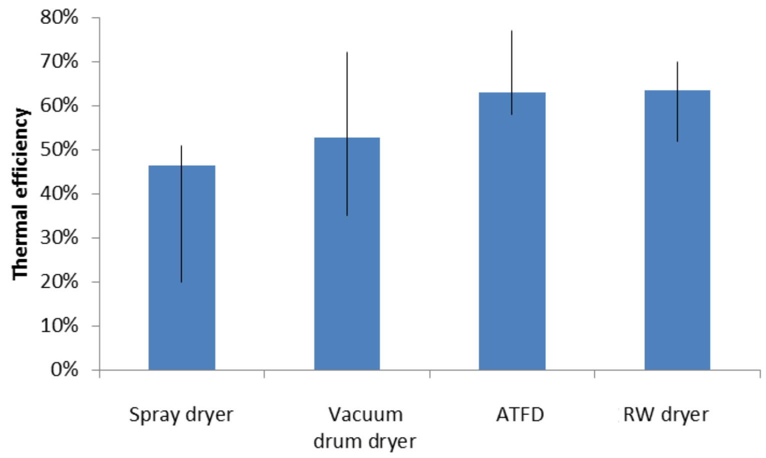
The results are also summarized in **Figure 13**. Most noticeable is the difference in primary energy use and the difference in heat use and electricity use. All thin film drying processes consume less primary energy compared to the spray drying process. This is mainly due to the fact that the thin film drying processes have a lower (final) heat demand. On the other hand the thin film drying processes have a higher (final) electricity demand compared to the spray drying, with vacuum drum drying having the highest final electricity use, which is mainly due to the high drive power.

Figure 13: Calculated energy use of all drying processes (results in energy/ton_ H_2O removed)



By dividing the energy demand needed for the evaporation of water (2,300 kJ/kg) by the calculated primary energy use, the thermal efficiency of the drying processes is calculated. The calculated thermal efficiencies of the drying processes are given in **Figure 14**. Visible is that ATFD and RW drying have the highest calculated thermal efficiency, which are also comparable, while vacuum drum drying has a somewhat lower calculated thermal efficiency. Along with the calculated thermal efficiency, also the bandwidth of thermal efficiencies found in literature is shown. It can be seen that all calculated thermal efficiencies fall within this bandwidth, with the calculated thermal efficiency of the spray dryer being on the high side, the vacuum drum dryer and RW dryer being in the middle and the ATFD being on the low side.

Figure 14: Calculated thermal efficiencies (blue bars) and thermal efficiencies obtained from literature (black lines) [31], [32].



4

Economic evaluation

The estimates for the capital expenditures (CAPEX) and operational expenditures (OPEX) are described in this chapter. The CAPEX are obtained from price quotes given by end-users, or else determined by a factorial method. The OPEX is based on the calculated energy costs and the investment costs.

4.1 CAPEX estimation

4.1.1 Spray drying

The CAPEX estimates for the spray dryer with different evaporation capacities are based on information given by equipment manufactures and end-users [18], [19], and are presented in **Table 9**. Cost prices are based on equipment only, meaning no engineering, construction and commissioning are taken into account. No fluidized bed drier is taken into account, except for the dewatering capacity of 5000 kg/h. Also for all capacities, building costs and costs for stairs, platforms, etc. are not taken into account. Investment costs are based on market prices of 2010, except for the dewatering capacity of 5000 kg/h (2015).

Table 9: Overview of different cost estimates for spray dryers

Dewatering capacity [kg/h]	15	22.5	30	45	60	200	500	5000
[1]FOB CAPEX [Meuro]	0.20	0.30	0.60	0.45	1.10	1.60	2.40	5.00

[1] Term of sale under which the price invoiced or quoted by a seller includes all charges up to placing the goods on board a ship at the port of departure specified by the buyer

It can be seen that for a typical dewatering capacity of 500 kg/hr the investment costs for a spray dryer is approximately 2.4 Meuro.

4.1.2 Vacuum drum drying

No cost data for vacuum drum drying could be obtained from manufacturers or end-users. A recent study of students of the University of Groningen (RUG), concerning a techno-economic analysis of a ATFD in comparison to a vacuum drum dryer [20], gives an estimate of the investment costs for the main equipment of a vacuum drum dryer with a dewatering capacity of 500 kg/h, determined by a factorial method [21].

The main equipment taken into account are:

- Centrifugal pump, for transportation of wet material
- Drum dryer, similar to atmospheric drum dryer
- Pressure vessels, for drum dryer and collection of solvent
- Condenser, for condensation of solvent from wet material

The vacuum pump was not taken into consideration due to the absence of reliable cost information. However, investment costs for a vacuum pump (for instance 70 mbar, 50 m^3/h) are calculated to be small (<15 k€) in comparison to the total Capex.

It is calculated that for a typical dewatering capacity of 500 kg/hr the investment costs for a vacuum drum dryer is approximately 1.35 Meuro. Using the same factorial method, the investment costs for different dewatering capacities is calculated. The results, along with calculated typical drying surface areas, can be found in **Table 10**.

Table 10: Overview of cost estimates for vacuum drum dryers (± 30% due to accuracy of the method)

Dewatering capacity [kg/h]	30	60	200	500	1000	1500
ISBL CAPEX [Meuro][1]	0.46	0.55	0.87	1.35	2.00	2.56
Drying surface area [m^2][2]	2	5	16	41	82	123

[1] Inside Battery Limits plant costs are the cost of procuring and installing all process equipment. ISBL costs include purchasing and shipping costs of equipment, land costs, infrastructure, piping, catalysts, and any other material needed for final plant operation, or construction of the plant.

[2] Calculated

Since Andritz Gouda (atmospheric) drum dryers comes in sizes ranging with drying surface of area of 0.75 m^2 up to 45 m^2 [25], a dewatering capacity of 500 kg/h seems to be a the maximum for a single/double drum dryer unit. Higher drying capacities given in **Table 10** should be looked at as indicative.

4.1.3 ATFD

The CAPEX estimates for the ATFD with different evaporation capacities along with typical drying surface areas are based on information given by BODEC [18], and are presented in **Table 11**. These investment costs are based on market prices of 2010. It can be seen that for a typical dewatering capacity of 500 kg/h, the investment cost is approximately 0.8 Meuro. Additional calculations showed that the expected investment cost for ISBL equipment for a ATFD with a dewatering capacity of 500 kg/h is in the order of 0.8 Meuro [20]. Included in this calculation are: ATFD, condenser, powder and distillate receiver, feed and distillate pump, interconnecting process piping and valves, instruments and structural cost. Excluded are: feed tanks, vacuum system, cleaning system, uploading and erection at site, insulation and steam under vacuum setup.

Table 11: Overview of different cost estimates for ATFD

Dewatering capacity [kg/h]	15	50	100	500	1000	1500
FOB CAPEX [Meuro][1]	0.10	0.20	0.45	0.80	1.35	1.60
Drying surface area [m2]	0.7[2]	2[2]	4.0[2]	18[1]	2x18[1]	2x25[1]

[1]BODEC, [2] Calculated

4.1.4 Refractance window drying

No cost data for RW-drying or Dry-on-water technology could be directly obtained from manufacturers (GW-dryer, Spiessens). However, a cost price estimate was provided by Nutrica Research, who got the estimate from an independent think tank company that profiled GW-dryer. GW-dryer mentions a cost price of 1,350,000 USD for their largest commercial unit (Model 5), which basically consists of five joint Model 1 units. Based on the given cost price and dewatering capacity [30] of the Model 5 unit, the cost price and dewatering capacity for the other Models are calculated. An overview of the cost estimated for different dewatering capacities can be seen in **Table 12**.

Table 12: Overview of different cost estimates for RW-dryers

	Model 1	Model 2	Model 3	calculated	Model 4	Model 5
Dewatering capacity [kg/h]	136	272	408	500	544	680[1]
FOB CAPEX [Meuro]	0.25	0.50	0.75	*0.92*	1.00	1.25[1]
Drying surface area [m2][2]	9	17	26	*32*	34	43[1]

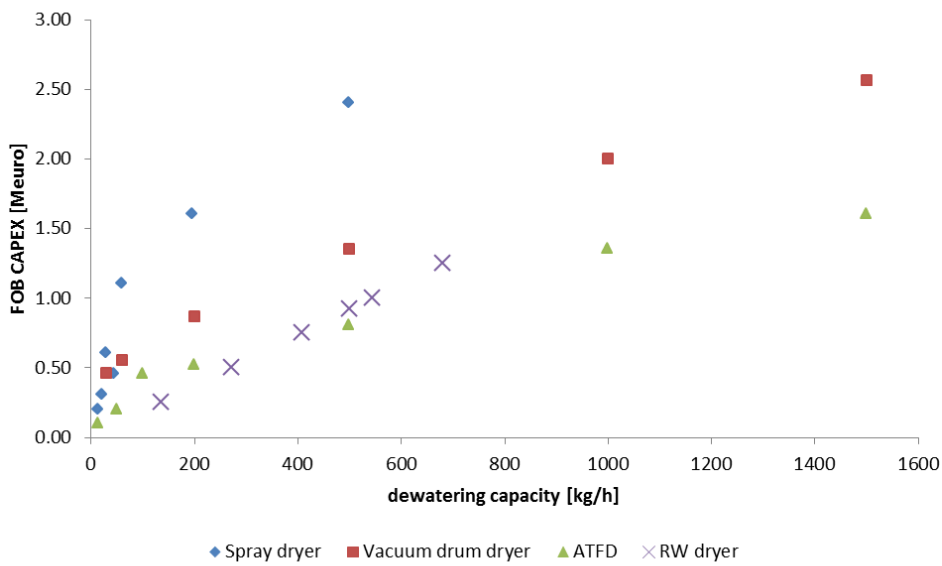
[1]GW-dryer, [2] Calculated

Since a separate unit has a specific dewatering capacity corresponding to Model 1, the cost price for other Models scales linearly to the dewatering capacity. Since only one application and removal area is used per total drying system, this does not apply to the drying surface area. Based on these figures it is calculated that for a specific dewatering capacity of 500 kg/h GW-dryer Model 4 is needed, resulting in an cost price of 1.0 Meuro.

4.2 CAPEX comparison

An overview of the CAPEX estimates for different dewatering capacities of the aforementioned drying processes is given in **Figure 15**. Based on this figure it can be concluded that for a dewatering capacity of 500 kg/h all thin film dryers have lower investment costs than the spray dryer. Although difference in investment costs between the thin film dryers exits, which might be a result of the different methods used for obtaining these figures, their mutual difference is less then compared to the spray dryer. At a dewatering capacity of 500 kg/h the investment cost for the ATFD and RW-dryer are in the same order of magnitude, where the vacuum drum dryer seems to be slightly more expensive. However, bear in mind that for the vacuum drum dryer the cost estimate accuracy is ± 30%, like mentioned in paragraph 4.1.2.

Figure 15: Overview of cost estimates for the reviewed dryers at different dewatering capacities



It can also be seen that where the other drying technologies benefits from economy of scale, this does not apply to the RW-dryer because of the mentioned modular buildup of separate individual modules.

4.3 OPEX estimation

The OPEX are the recurring cost necessary to operate the drying facilities. The following cost categories can be distinguished:

1. Personnel;
2. Maintenance;
3. Energy.

No figures were obtained for personnel costs. It is known that quite considerable amounts of time are spend on cleaning the installations in spray drying operations. However, for the reviewed thin film drying processes this is unknown. Therefore no personnel costs estimate is given. For maintenance sometimes a fixed percentage of the total investment costs is used, as is also the case in this study. The energy costs are directly related to the drying process and are made up of costs for fuels spend to generate the necessary heat for evaporating the water and costs for electricity used for driving drums, rotors, belts, pumps, fans, etcetera. The fuel and electricity used for the reviewed drying processes can be found in paragraph 3.3

4.4 OPEX comparison

The OPEX is calculated for a year assuming a dewatering capacity of 500 kg per hour and operational time of 7000 hours per year. The results are summarized in **Table 13**. An overview of all assumptions used is given below:

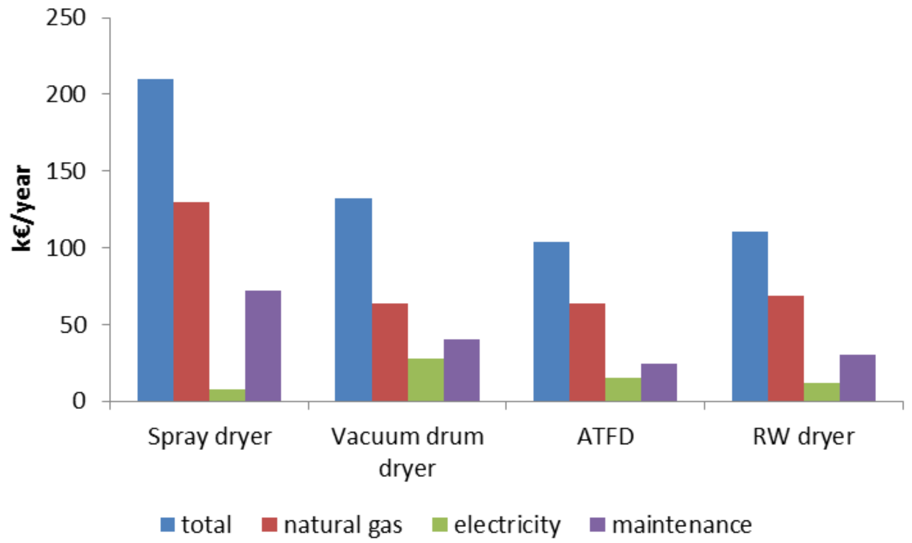
- Gas price : 7 €/GJ (ICE ENDEX, TTF GAS)
- Electricity price : 40 €/MWh (APX-EPEX NL)
- Operating hours : 7000 hours/year
- Dewatering capacity : 500 kg/hr
- Maintenance : 3% of investment costs

Table 13: Overview of calculated operational costs estimates of the reviewed drying processes

	Spray dryer	Vacuum drum dryer	ATFD	RW dryer
Natural gas [k€/yr]	130.1	63.9	63.9	68.5
Electricity [k€/yr]	7.6	27.9	15.6	11.5
Maintenance [k€/yr]	72	41	24	30
Total [k€/yr]	**209.8**	**132.4**	**103.5**	**110.1**

The results are also visualized in **Figure 16**. As could be expected from the energy use calculations, the energy costs for the thin film drying processes are lower compared to the spray drying process. Comparing the thin film drying processes mutually it can be seen that, due to the somewhat higher electricity use, the vacuum drum drying process has higher operational costs than the ATFD and RW drying process.

Figure 16: Overview of the operational cost estimates of reviewed drying processes (500 kg H_2O/h)



Keep in mind that the analysis above is very sensitive to the assumed energy prices, which will be subject to change in the future.

5

Conclusions

Spray drying and thin film drying are two different kind of drying techniques with not only their own distinct heat transfer mechanism, but also with difference in type of feedstock (like suspension, emulsion, % dry matter) and finished product. Therefore, comparing the primary energy use of these drying processes can only be achieved by calculating the primary energy use per ton water removed.

Concerning Refractance Window drying, recent insights on the underlying thermo-dynamics of the process show that the main modus of heat transfer (99% of the heat flux) is conduction instead of the assumed infrared radiation.

Based on the calculations performed and the assumptions used, it can be concluded that vacuum drum drying, ATFD and RW-drying have lower primary energy use than spray drying. Where literature mentions savings in primary energy in the range of 40% compared to spray drying, present calculations show that a reduction in the range of 15% to 30% is more likely. This energy reduction is related to the fact that spray drying is a convective drying technology, where intake air is heated up to high(er) temperature in order to take up as much evaporated water as possible. Besides this, also avoiding the 'sticky phase' in spray drying can force less energy efficient process conditions.

Reductions in CAPEX are expected for the reviewed thin film dryers as a result of redundant feed and atomization, intake air heating and exhaust air handling equipment compared to spray drying. For a drying capacity of 500 kg/h, a reduction in CAPEX between € 1.05 million and € 1.6 million can be expected for the evaluated thin film dryers compared to a spray dryer, corresponding to a CAPEX reduction of 45% to 65%.

Regarding the operational costs (OPEX), only energy- and maintenance costs are taken into account, where the assumed maintenance cost are a fixed percentage of the total investment costs. For the mentioned drying capacity of 500 kg/h, a yearly reduction in OPEX between k€ 77 and k€ 106 can be expected for the evaluated thin film dryers compared to a spray dryer, corresponding to a OPEX reduction of 37% to 50%.

This analysis holds for the present situation with respect to the electricity system and energy prices. Future changes in this situation will require a reassessment.

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Appendix A. Detailed mass and energy balances

Spray drying process (evap. cap. 1000 kg/h)

Spray dryer

	mass		energy		exergy	
	in	out	in	out	in	out
	product and air					
product		1.02		0.14		0.01
feedstock	2.00		0.29		0.01	
supply air	20.1		4.46		0.96	
exhaust air		21.1		4.52		0.36
infiltration air	0.00		0		0.00	
exfiltration air		0.00		0		0.00
heat loss				0.14		
heat steam direct			0.00			
heat hot water boiler			0.00			
elektricity microwave, ir, etc			0.00			
elektricity fans, conveyers, etc			0.04			
	22.1	22.1	4.79	4.79	0.97	0.37

Fluidized bed dryer

	mass		energy		exergy	
	in	out	in	out	in	out
	product and air					
product		1.00		0.06		0
feedstock	1.02		0.14		0.01	
supply air	5.4		0.24		0.00	
exhaust air		5.4		0.32		0.01
infiltration air	0.00		0		0.00	
exfiltration air		0.00		0		0.00
heat loss				0.00		
heat steam direct			0.00			
heat hot water boiler			0.00			
elektricity microwave, ir, etc			0.00			
elektricity fans, conveyers, etc			0.01			
	6.4	6.4	0.38	0.38	0.01	0.01

Spray dryer and fluidized bed dryer

	specific energy uses					
	GJ/ton$_{powder}$			GJ/ton$_{evaporated\ water}$		
	tower	fluid.bed	total	tower	fluid.bed	total
heat	4.0	0.1	4.1	4.0	5.0	4.1
nat.gas	4.7	0.1	4.8	4.8	5.4	4.8
electricity	0.1	0.0	0.1	0.1	1.0	0.1
fuels	4.9	0.2	5.0	5.0	7.7	5.0

Vacuum drum drying process (evap. cap. 500 kg/h)

	mass		energy		exergy	
	in	out	in	out	in	out
	product and air					
product		0.14		0.02		0.00
feedstock	0.64		0.05		0	
product vapor		0.49		1.25		1.19
infiltration air	0.01		0.00		0.00	
exfiltration air		0.02		0.03		0.00
heat loss				0.07		
Qutilities			1.31			
elektricity fans, conveyers, etc			0.00			
	0.65	0.65	1.36	1.36	0.00	1.19

heat (final)	GJ
steam	1.31
hot water boiler	0.00
	1.31

electricity (final)	kWh	MJ
Pel;vacuum pump	26.3	95
Pel;drive	73.3	264
	100	358

Fuels (primary)	GJ
steam boiler	1.38
hot water boiler	0.00
power plant	0.80
	2.18

product production	0.14	ton	90% d.m.
evaporation load	0.50	ton	
specific heat use	2.63	GJ/ton_{water}	
specific electricity use	199	kWh/ton_{water}	
specific fuel use	**4.36**	GJ/ton_{water}	
steam consumption	1.15	kg steam/kg_water	
thermal efficiency	53%		

ATFD process (evap. cap. 500 kg/h)

	mass in	mass out	energy in	energy out	exergy in	exergy out
product and air						
product		0.14		0.02		0
feedstock	0.64		0.05		0	
product vapor		0.50		1.28		1.21
infiltration air	0.00		0.00		0.00	
exfiltration air		0.00		0		0.00
heat loss				0.07		
Qutilities			1.31			
elektricity fans, conveyers, etc			0.00			
	0.64	0.64	1.36	1.36	0.00	1.21

heat (final)	GJ
steam	1.31
hot water boiler	0.00
	1.31

electricity (final)	kWh
Pel;vacuum pump	26.3
elektricity drive power, etc	29.4
	56

Fuels (primary)	GJ
steam boiler	1.38
hot water boiler	0.00
power plant	0.45
	1.83

product production	0.14	ton	90% d.m.
evaporation load	0.50	ton	

specific heat use	2.63	GJ/ton_{water}
specific electricity use	111	kWh/ton_{water}
specific fuel use	**3.66**	GJ/ton_{water}

steam consumption 1.15 kg steam/kg_water

thermal efficiency 63%

Refractance Window process (evap. cap. 500 kg/h)

	mass in	mass out	energy in	energy out	exergy in	exergy out
	product and air					
product		0.14		0.02		0
feedstock	0.64		0.05		0	
supply air	45.9		2.31		0.03	
exhaust air		46.4		3.67		0.09
heat loss				0.07		
Qutilities			1.40			
elektricity fans, conveyers, etc			0.00			
	46.6	46.6	3.8	3.8	0.03	0.09

heat (final)	GJ
steam	0.00
hot water boiler	1.41
	1.41

electricity (final)	kWh	MJ
Pel;blower	8.8	32
Pel;pump	1.9	7
Pel;others	30.5	110
	41.2	148

Fuels (primary)	GJ
steam boiler	0.00
hot water boiler	1.48
power plant	0.33
	1.81

product production	0.14	ton	90% d.m.
evaporation load	0.50	ton	
specific heat use	2.81	GJ/ton_{water}	
specific electricity use	82	kWh/ton_{water}	
specific fuel use	**3.62**	GJ/ton_{water}	
hot water consumption	33.42	kg water/kg_water	
steam consumption	0.00	kg steam/kg_water	
thermal efficiency	63%		

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