Drying technologies

11/08/25

MEMBER OF ATH

Agenda

1. Introduction
2. Introduction thermal drying
3. Basics mass + heat transfer
4. Typical solvents
5. Industrial drying systems
6. Summary

1.

Introduction

Coatema® Coating Machinery GmbH

Overview

Quality
made in Germany

Innovations

Part of the ATH Holding

S2S equipment

R2R equipment

Bespoke equipment

Coating

Printing

Laminating

Founded
1974

Printed electronics
Fuel cells
Membranes
Pharmaceutics
Solar
Batteries
Prepregs
Green Hydrogen

From lab 2 fab

R&D
projects & network

Worldwide
service

Group of companies

ALTONAER
TECHNOLOGIE
HOLDING

KROENERT

- ✓ Founded 1903
- ✓ Approx. 200 employees
- ✓ Located in Hamburg

DRYTEC

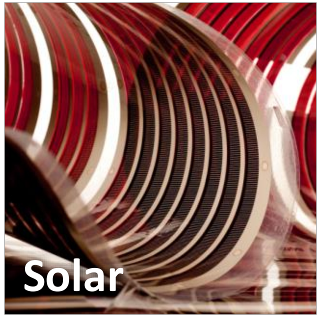
- ✓ Founded 1995
- ✓ Approx. 50 employees
- ✓ Located in Norderstedt

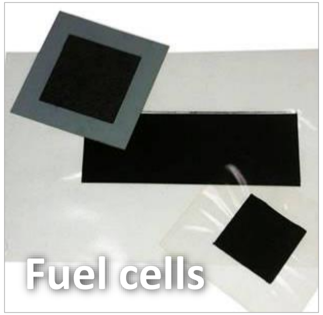
Coatema® Coating Machinery GmbH

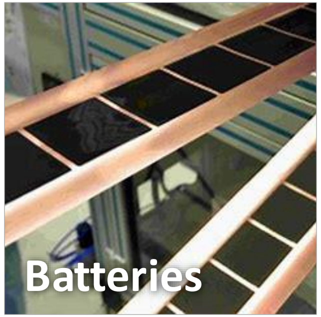
- ✓ Founded 1974
- ✓ Approx. 50 employees
- ✓ Located in Dormagen

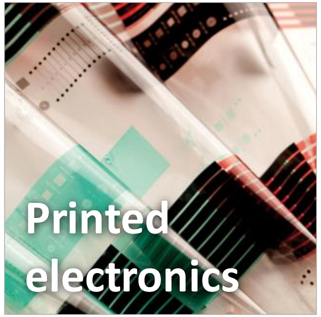
Represented worldwide

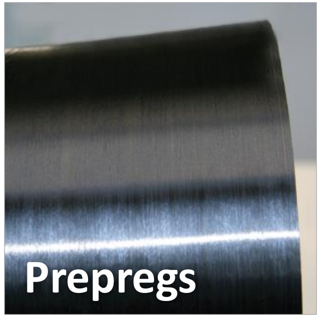
Our markets





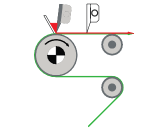




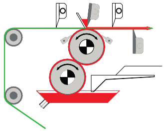


and more

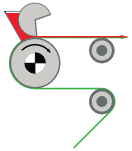
Coating systems



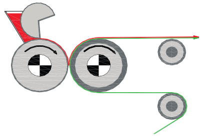
Knife system



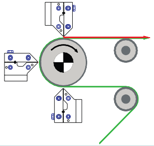
Double side coating system



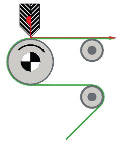
Commabar system



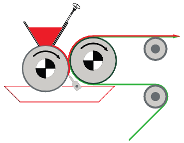
Reverse commabar system



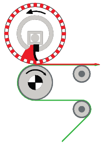
Slot die system



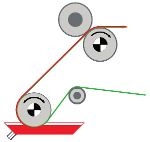
Curtain coating system



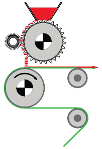
Case knife system



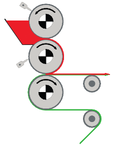
Rotary screen system



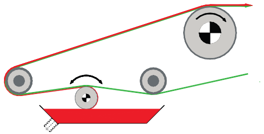
Dipping system (Foulard)



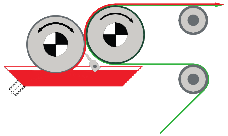
Powder scattering system



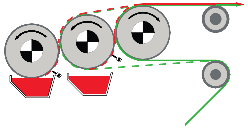
Reverse roll coating system



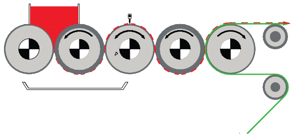
Micro roller coating system



2-roller coating system

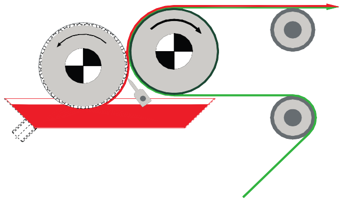


3-roller combi coating system

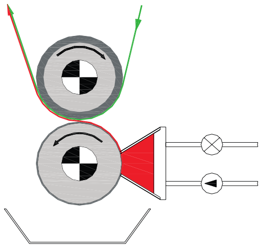


5-roller coating system

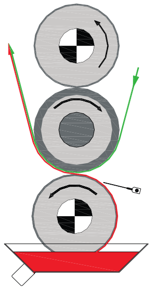
Printing systems



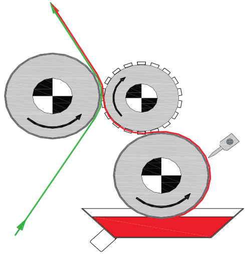
Engraved roller system



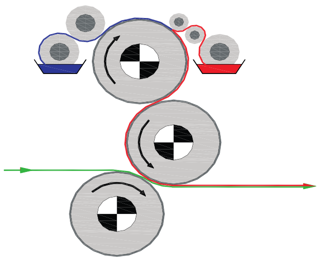
Gravure roller system



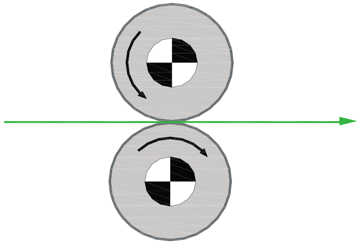
Gravure indirect system



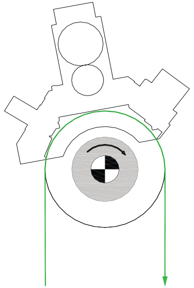
Flexography system



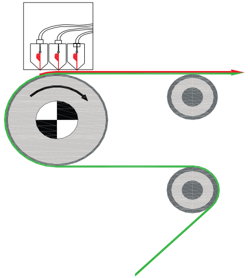
Offset lithography system



Hot embossing system



Nanoimprint system



Inkjet system

Our work in associations – global networking

Board Member:
OE-A

Advisory Board:
Fraunhofer ITA

Coatema® Coating Machinery GmbH

Coatema customers

GUMOTEX
EVONIK INDUSTRIES
covestro
SAMSUNG
DAIMLER
era
SEKISUI alveo
ASTORPLAST
BIERBAUM UNTERNEHMENSGRUPPE seit 1895
Continental CONTITECH
analyticon
TDK
BASF We create chemistry
FREUDENBERG INNOVATING TOGETHER
HÜBNER
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DELTA
SolarIntegrated An Energy Conversion Devices Company
Scheuten
M EN SHU
LTS TRANSDERMAL. MARKETLEADER.
SCHERING making medicine work
SARTORIUS
HARTMANN
Hydro
habasit
stahl
3P InkJet Textiles AKTIENGESELLSCHAFT
ionity

Coatema®
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R&D customers

Technische Universität Dresden
KIT Karlsruhe Institute of Technology
Agency for Science, Technology and Research Singapore
The University of Arizona
UNSW Sydney
Queen Mary University of London
Aristotle University of Thessaloniki
TTRI Taiwan Textile Reasarch Institute
ITA Institut für Textiltechnik und Lehrstuhl für Textilmaschinenbau
RWTH Aachen University
NREL Transforming ENERGY
Ruhr Universität Bochum RUB
Technical University of Liberec www.tul.cz
hochschule hof University of Applied Sciences
Deutsches Textilforschungszentrum Nord-West German Textile Research Centre North-West
cea
CSIRO
Fachhochschule Kiel Hochschule für Angewandte Wissenschaften
CeNTI Centre for Nanotechnology and Smart Materials
FILK Forschungsinstitut Leder und Kunststoffbahnen
The Ohio State University
Hochschule Niederrhein University of Applied Sciences
Georgia Institute of Technology
University of Cambridge
Neue Materialien Fürth
Joanneum Research
Heriot Watt University
SW
DITF Deutsche Institute für Textil+Faserforschung
Jülich Forschungszentrum
National University of Mongolia
VTT
TNO innovation for life
eurecat Centre Tecnològic de Catalunya
Fraunhofer IMM
Fraunhofer LBF
KITECH Korea Institute of Industrial Technology
Holst Centre Open Innovation by imec and TNO
Hochschule Reutlingen Reutlingen University
tecnalia
Fraunhofer IAP
Fraunhofer IAF
Fraunhofer ILT
Fraunhofer IFAM
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Fraunhofer ISE
Fraunhofer ICT
Fraunhofer PYCO
Fraunhofer IPT
Fraunhofer IWM

Coatema® Coating Machinery GmbH

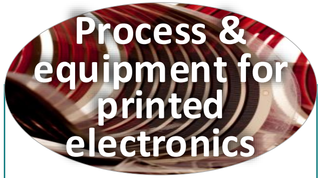
R&D projects overview 2022 – 2025

REAL NANO

In-line and real-time digital nano-characterization for flexible organic electronics

NOUVEAU

The NOUVEAU project will develop solid oxide cells (SOCs) with innovative La- and PMG-free electrode materials

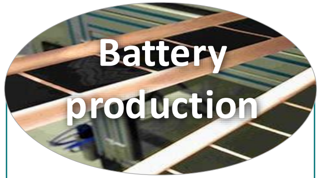


FLEX2ENERGY
AUTOMATED MANUFACTURING PRODUCTION LINE FOR IPVS

R2R production line for OPV solar with integrated backend

FLEX-G 4.0

Upscaling and development of EC based switchable films to decrease energy use in buildings



IDEEL

Implementation of laser drying processes for lithium-ion battery production

SOLiD

R2R process optimization for solid state batteries

PEP LAT

Plasmonically enhanced photocatalysis for wastewater treatment

ROLL 2 SOL

R2R nanostructuring of functional films

WATER PROOF

The WaterProof project aims at developing an electrochemical process that converts CO_2 emission

FLEX FUNCTION 2 SUSTAIN

Creating an open-innovation testbed for sustainable packaging

2.

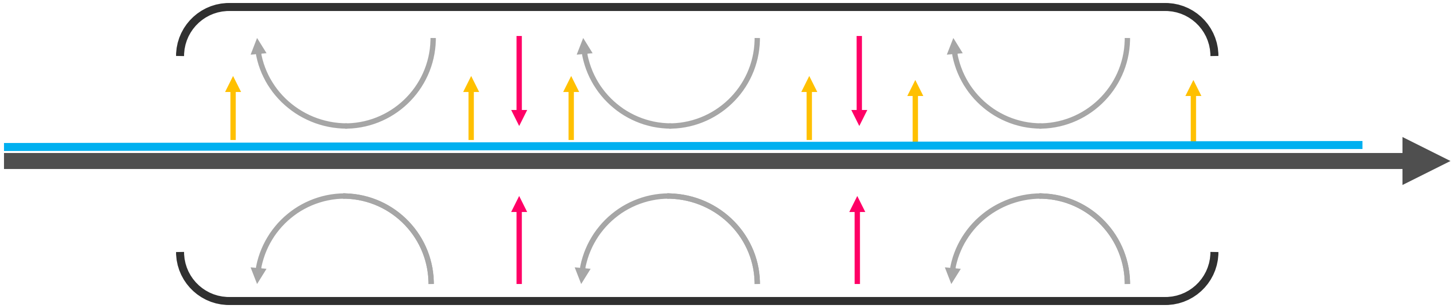
Introduction thermal drying

Coating parameters

Coating chemistry	Coating processes	Process control	Drying
✓ Rheology ✓ Viscosity ✓ Viscoelasticity ✓ Type of solvents ✓ Solid content ✓ Van der Waals force ✓ Sheer ratio ✓ Adhesion/Cohesion	✓ Coating systems ✓ Single or multilayer coatings ✓ Direct coatings ✓ Transfer (indirect) coatings ✓ Substrate speed ✓ Layer thickness ✓ Coating accuracy	✓ Process layout ✓ Tension control system ✓ Material guiding system ✓ Inline parameter control ✓ Quality control	✓ Convection drying ✓ Contact drying ✓ Infrared drying ✓ Sintering ✓ NIR ✓ High frequency ✓ UV crosslinking systems

Substrate	Pretreatment	Environment	Finishing
✓ Surface tension ✓ Dimension stability ✓ Surface structure ✓ Contact angle	✓ Corona ✓ Plasma ✓ Cleaning	✓ Humidity ✓ Temperature ✓ Inert conditions	✓ Calendaring ✓ Embossing ✓ Slitting

Thermal Drying – As general as possible(!?)



- ✓ Heat Conduction/ Heat Diffusion
- ✓ Heat Convection/ **Mass Transfer**
- ✓ Radiation

Substrate
Coating
Heat transfer
Evaporating solvent
Solvent vapor transfer

Mass Transfer

3.

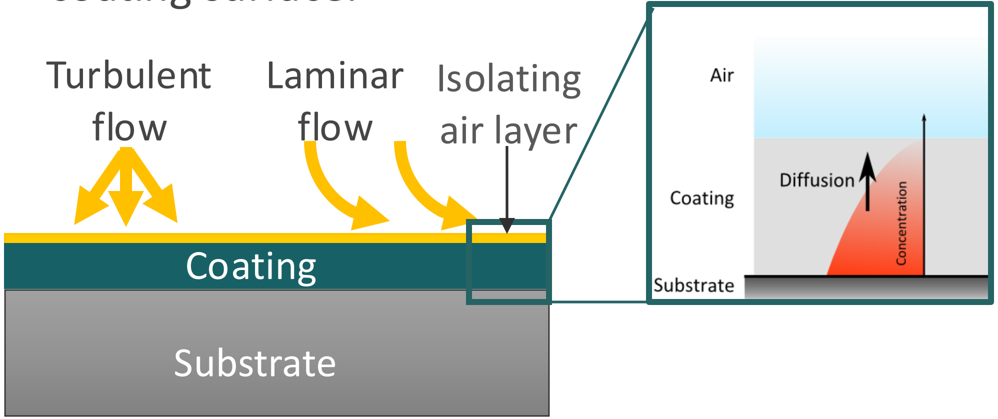
Basics
mass + heat transfer

Drying dynamics: The Boundary Layer

An isolating air layer forms just on top of the coated film

✓ Without convection mass+heat transfer is limited to diffusion and therefore slow.

✓ Convective (laminar or turbulent) flow needs to be applied without sacrificing the coating surface.



Usually there is a trade-off:

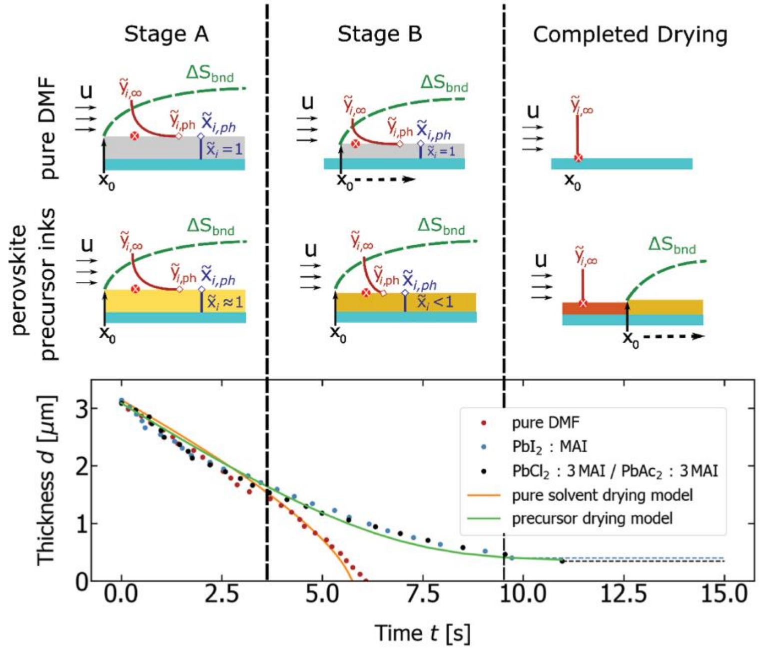
effective fast heat/mass transfer
or
gentle mild slow drying

Drying dynamics: Mass Transfer with a Heat Plate

- ✓ Constant temperature
- ✓ General equation for mass transfer:

$$\frac{\dot{m}}{A} = h_m \Delta c_{\mathrm{bnd}}$$

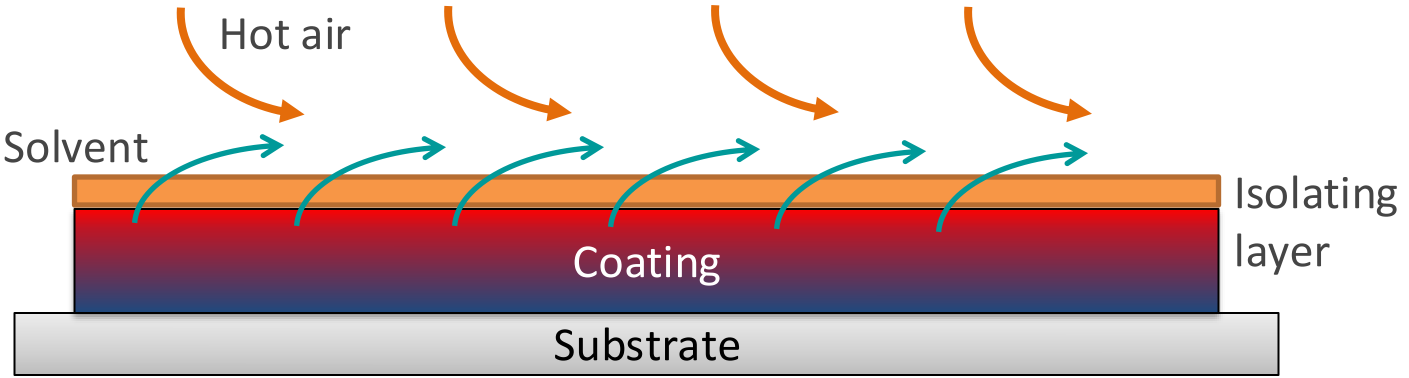
- ✓ with $\Delta c_{\mathrm{bnd}} \approx \frac{a_{\mathrm{Sol}} M_{\mathrm{sol}} \cdot e^{\left(A + \frac{B}{C + T_{\mathrm{surf}}}\right)}}{R \cdot T_{\mathrm{surf}}}$
- ✓ The Antoine Parameters A, B and C can be found for a variety of solvents
- ✓ Solvent-Solute-Interaction a_{Sol} slows mass transfer



Ternes, S. *et al. Adv. Energy Mater.* **9**, 1901581 (2019)

Drying dynamics: Hot air drying

- ✓ Heating and vapor transport combined
- ✓ Bulk heating by thermal conductivity from surface
- ✓ Isolating layer to be overcome by air flow
- ✓ High air flow deteriorates surface
- ✓ Temperature easy to limit
- ✓ Slow



Hot air drying: Heat transfer

✓ The heat transfer coefficient h_q describes energy transfer from hot air to liquid surface via:

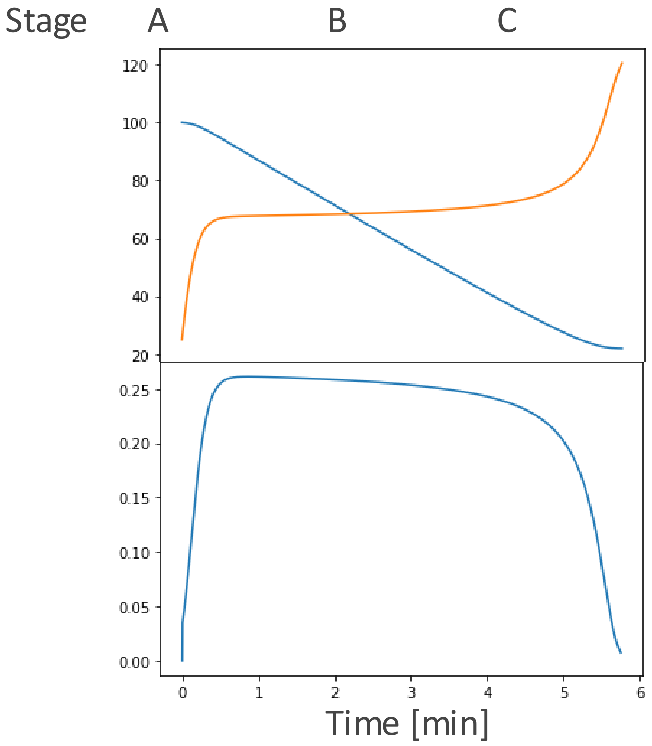
$$\dot{q}_{\mathrm{in}} = h_q(T_{\mathrm{surf}} - T_{\mathrm{air}})$$

✓ Evaporating solvent takes energy with it:

$$\dot{q}_{\mathrm{out}} = \frac{\dot{m}}{A}\left(c_p T_{\mathrm{surf}} + \frac{\Delta H_{\mathrm{vap}}}{M_{\mathrm{sol}}}\right)$$

✓ Surface Temperature T_{surf} balances itself in Stage B of drying process and rises in the other ones

✓ Solvent-Solute-Interaction a_{Sol} slows mass transfer



Drying dynamics: Calculation example

This is a practical example of a real calculation of dryer length for a 900 µm wet coating based on solvent xylene at drying temperature 120°C.

Sufficient energy transfer is supposed.

The result was verified by trial.

Coating data:	
Coating thickness wet	900 µm
Solvent xylene	65%
Pure solvent thickness wet	585 µm
Specific weight xylene	0.88 g/cm³
Solvent grammage	514.8 g/m²
Web speed	0.13 m/min
Evaporation data:	
Vapor pressure xylene at 20°C	880 Pa
Boiling temperature xylene	140°C
Vapor pressure at 120°C	56180 Pa
Relative molar mass xylene	106.17
Evaporation rate (according to Coatema method)	1.64 g/m²s
Result (from web speed, grammage, evaporation rate):	
Dryer length	0.68 m

Nothing is as easy as it seems: Transfer-Coefficients

- ✓ The heat transfer and mass transfer coefficients are not constant!
  They are temperature and air velocity dependent
- ✓ Nußelt-, Schmidt-, Sherwood-, Prandtl- and Reynolds number are necessary to empirically describe the transfer coefficients in each dryer configuration

$$h_m = \frac{\mathrm{Sh} \cdot D_{m,\mathrm{air-Sol}}}{L} \qquad h_q = \frac{\mathrm{Nu} \cdot \lambda_{\mathrm{air-Sol}}}{L}$$

$$\mathrm{Sh} = A \cdot \mathrm{Sc}^B \mathrm{Re}^C \qquad \mathrm{Nu} = A \cdot \mathrm{Pr}^B \mathrm{Re}^C$$

- ✓ A, B and C can be found in literature or determined experimentally

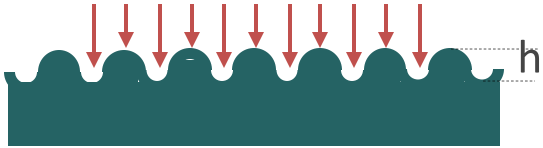
Nothing is as easy as it seems: Surface deterioration

- ✓ Air flow removing the evaporating solvent may be laminar or turbulent.
  Fluctuations of the flow may deteriorate the surface of a low viscous liquid causing wavy or stochastic structures.
- ✓ For rough estimation it may be assumed, that 10% fluctuations of the dynamic (impact) pressure of the air flow compensate the hydrostatic pressure difference caused by surface structures of the low viscous liquid:

$$10\rho_{liquid} \cdot g \cdot h = 1/2 \cdot \rho_{air} \cdot vmax^2 \qquad v_{max} = \sqrt{20\left(\frac{\rho_{liquid}}{\rho_{air}}\right) g \cdot h}$$

→ Result: orange skin of 1 µm deterioration depth would be created by an air flow of 0.5 m/sec with superimposed fluctuations of 10%.

Nonuniform air flow with 10% fluctuations

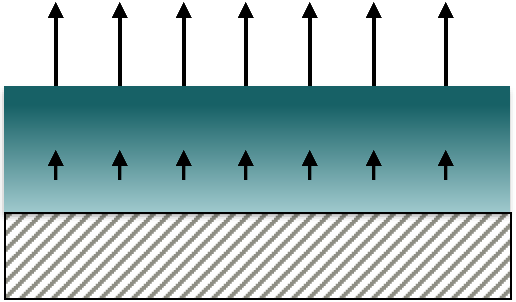


Coating with orange skin surface (exaggerated)

Dynamic effects being influenced by viscosity are not calculated.
So the estimation holds for very low viscous liquids only.

Nothing is as easy as it seems: Diffusion limit and skinning

- ✓ Drying is also limited by solvent diffusion
  (at least in the final state of low residual solvent content).
- ✓ If the internal diffusion is slower than the evaporation from the surface, then a skin may be created.
- ✓ The skin acts as a barrier. The remaining diffusion through the skin may be slower than the wet diffusion by many orders of magnitude.



So the initial evaporation must be reduced by low temperature and/or by partially saturated atmosphere. Despite reduced evaporation the total drying time then may be shorter than at full initial evaporation.

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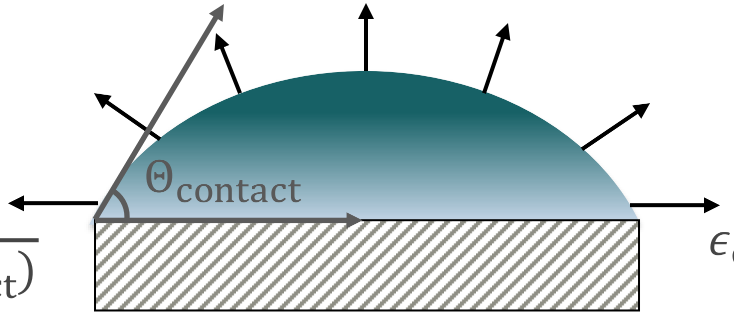
Nothing is as easy as it seems: Printed dots

- ✓ A printed dot has a different surface area than a continuous film
- ✓ Correction for the higher surface area needs to be made dependent on contact angle
- ✓ Incident direction of Air must be taken into account for effective Area
- ✓ Drops do not have homogeneous thickness (Absorption)

$$\epsilon_{corr} = \frac{2}{(1 + \cos \Theta_{contact})}$$

$$0° \leq \Theta_{contact} \leq 90°$$

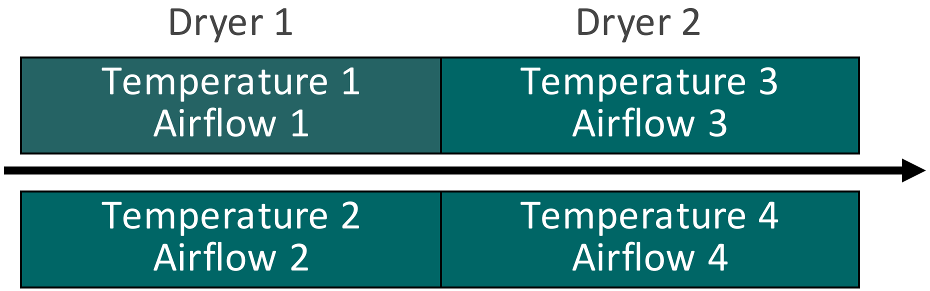


$$\epsilon_{corr} = 2 - 2 \cos \Theta_{contact}$$

$$90° \leq \Theta_{contact} \leq 180°$$

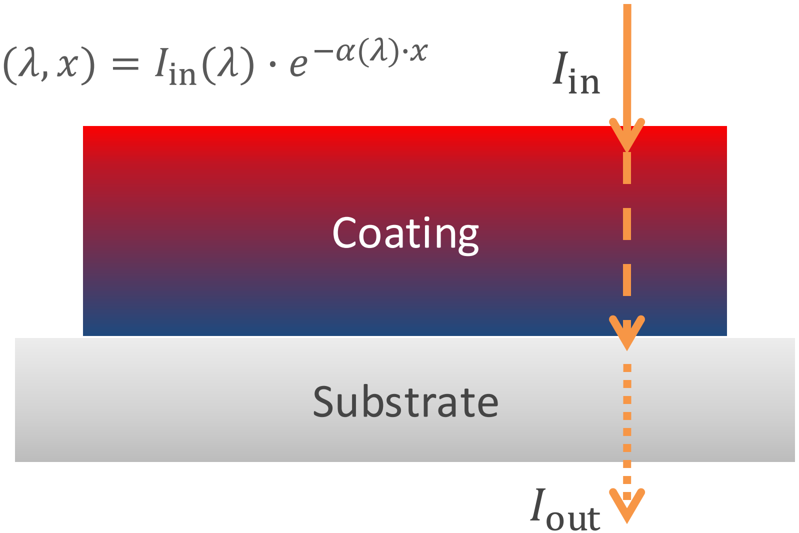
Drying dynamics: Drying zone design

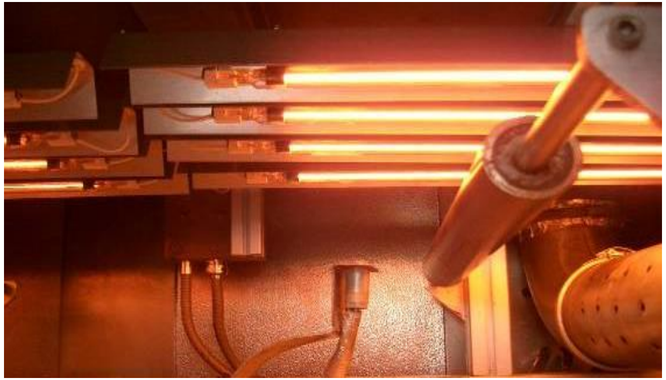
- ✓ Downweb temperature profiles can be realized by partitioning the dryer in different zones with different drying parameters.
- ✓ But temperature uniformity is difficult.
  Possible cause: Mixing of hot and cool air at unintended leakages by Venturi effect.
- ✓ Experience shows, that there is always a compromise:
  Good temperature uniformity requires low homogeneous air flow. High air flow results in less temperature uniformity.



(N)IR technology

$$I(\lambda, x) = I_{in}(\lambda) \cdot e^{-\alpha(\lambda) \cdot x}$$

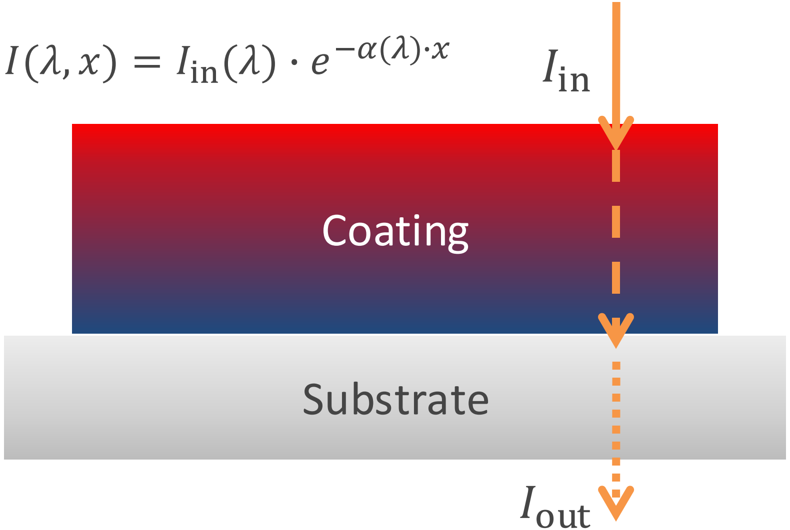




$I_{in}(\lambda)$	Intensity in
I_{out}	Intensity out
$\alpha(\lambda)$	Absorption coefficient
d	Layer thickness

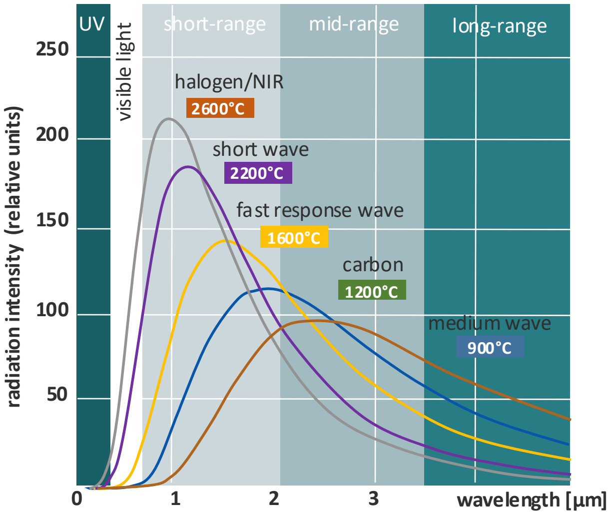
(N)IR technology

$$I(\lambda, x) = I_{in}(\lambda) \cdot e^{-\alpha(\lambda) \cdot x}$$



$I_{in}(\lambda)$	Intensity in
I_{out}	Intensity out
$\alpha(\lambda)$	Absorption coefficient
d	Layer thickness

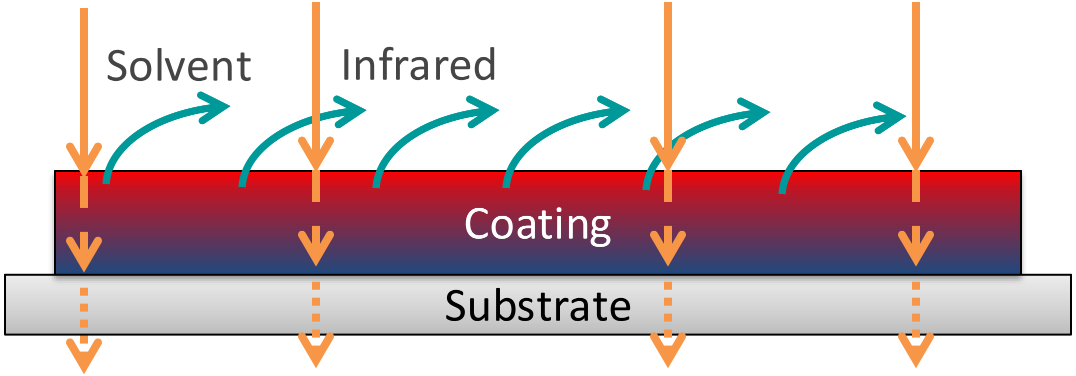
High absorption | Optimum absorption | Low absorption



Relative intensity of radiators at different wavelengths

(N)IR overview

- ✓ Heat and mass transport separated
- ✓ Selective bulk heating by absorption
- ✓ Absorption and emission dependent on the wavelength
- ✓ Overheating and uniformity to be controlled
- ✓ Fast, if applicable
- ✓ Wavelength range 780 nm – 3 µm



4.

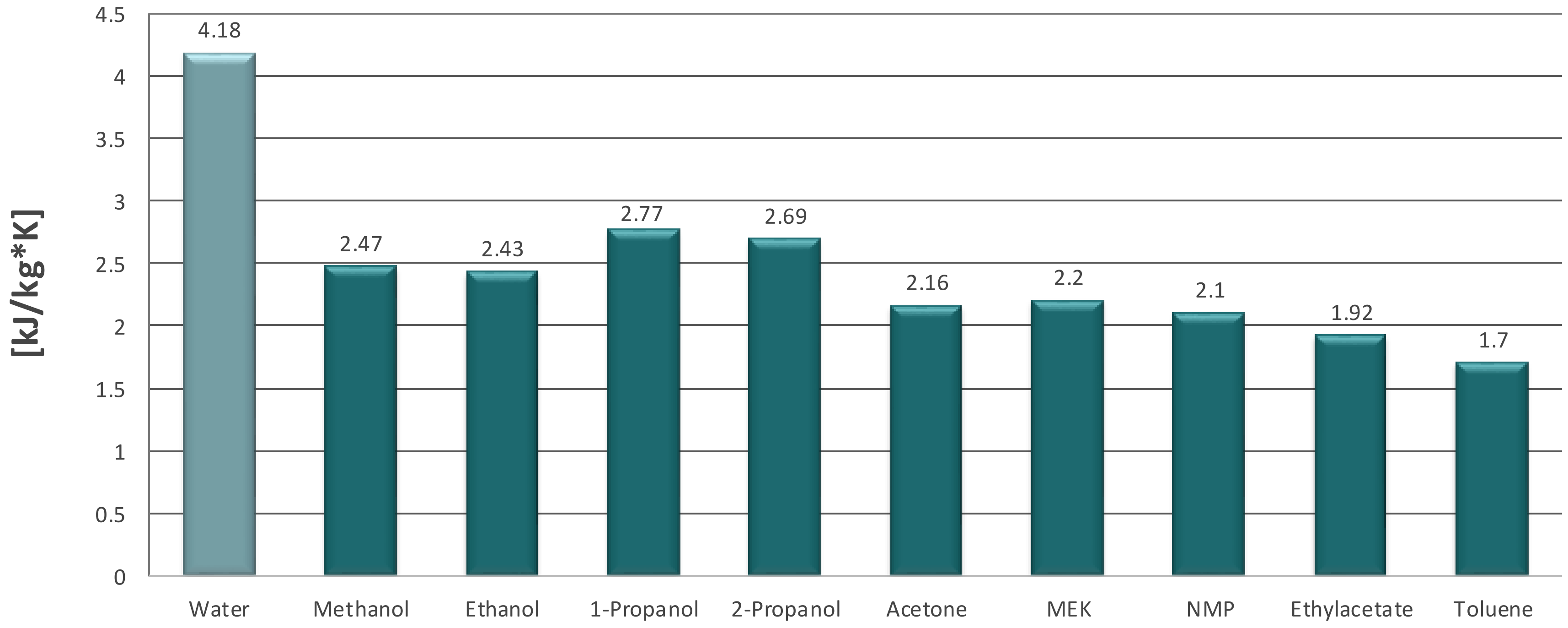
Typical solvents

Overview

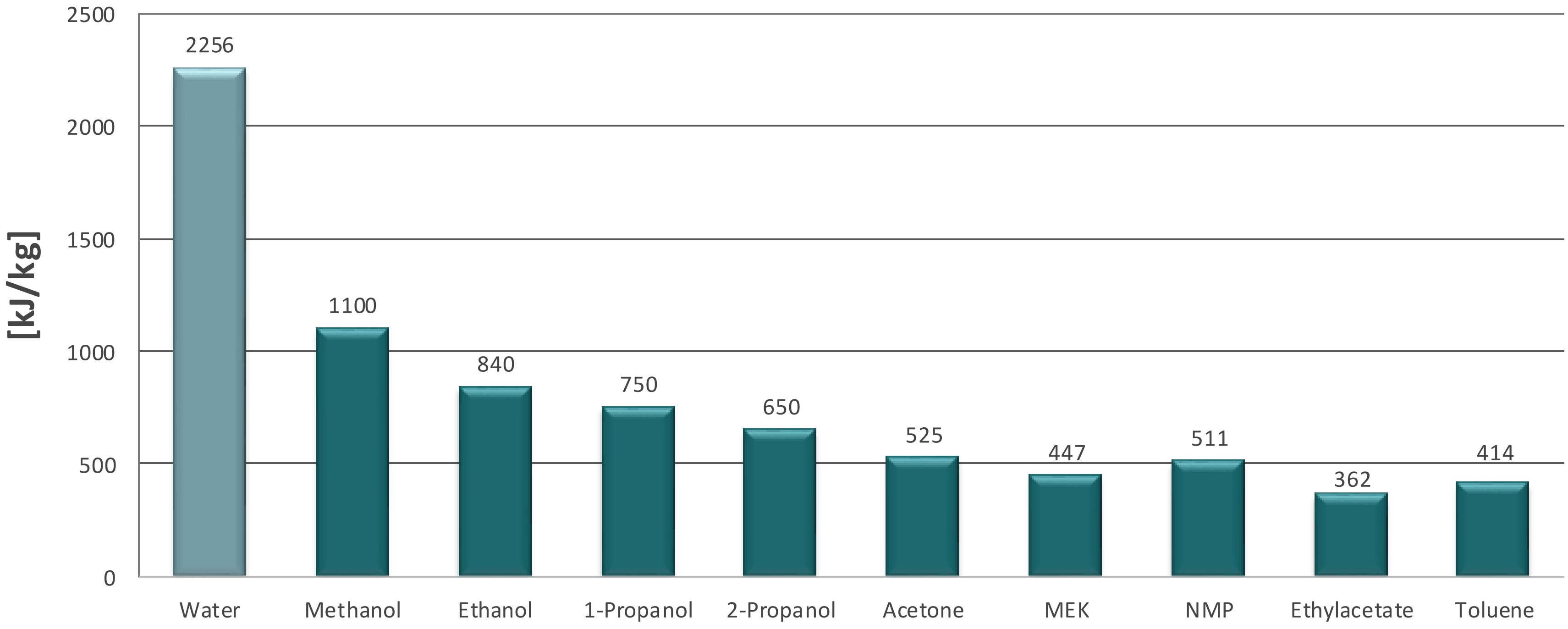
Solvent	Molar mass (g/mol)	Boiling point (°C)	Vapor pressure at 20°C (mbar)	Vapor pressure at 50°C (mbar)	Evaporation energy (kJ/kg)	Heat capacity (kJ/kg*K)	Surface energy at 20°C (mN/m=dyn/cm)
Water	18	100	23	123	2256	4.2	71.9
Methanol	32	65	129	535	1100	2.5	22.5
Ethanol	46	78	59	280	840	2.4	21.6
1-Proponol	60	97	20	112	750	2.8	23.0
2-Proponol	60	82	43	225	650	2.7	21.0
Acetone	58	56	246	830	525	2.2	22.8
MEK	72	80	105	373	447	2.2	24.6
NMP	99	203	0.3	2.9	511	2.1	40.9
Ethylacetate	88	77	98	380	362	1.9	23.0
Toluene	92	111	29	124	414	1.7	28.5

no guaranty

Heat capacity



Evaporation energy



5.

Industrial drying systems

Information needed to properly select and size a drying system

Information about the substrate

- ✓ Web weight – weight per unit area
- ✓ Web material
- ✓ Specific heat of web
- ✓ Temperature limitations
- ✓ Operating web tension – tension sensitivity
- ✓ Special characteristics

Soucre: Drytec

Information needed to properly select and size a drying system

Information about the environment

Details on the ambient conditions:

- ✓ Climatic conditions (ambient temperature, air moisture, etc.)
- ✓ Local conditions (geodetic height, size of the work hall)
- ✓ National guidelines (EN 1539, NFPA, etc.)

Details on peripherical systems:

- ✓ Air treatment facilities
- ✓ Energy supply (gas, steam, electrical energy)
- ✓ Compressed air supply
- ✓ Energy recovery facilities

Soucre: Drytec

Operation modes for drying systems

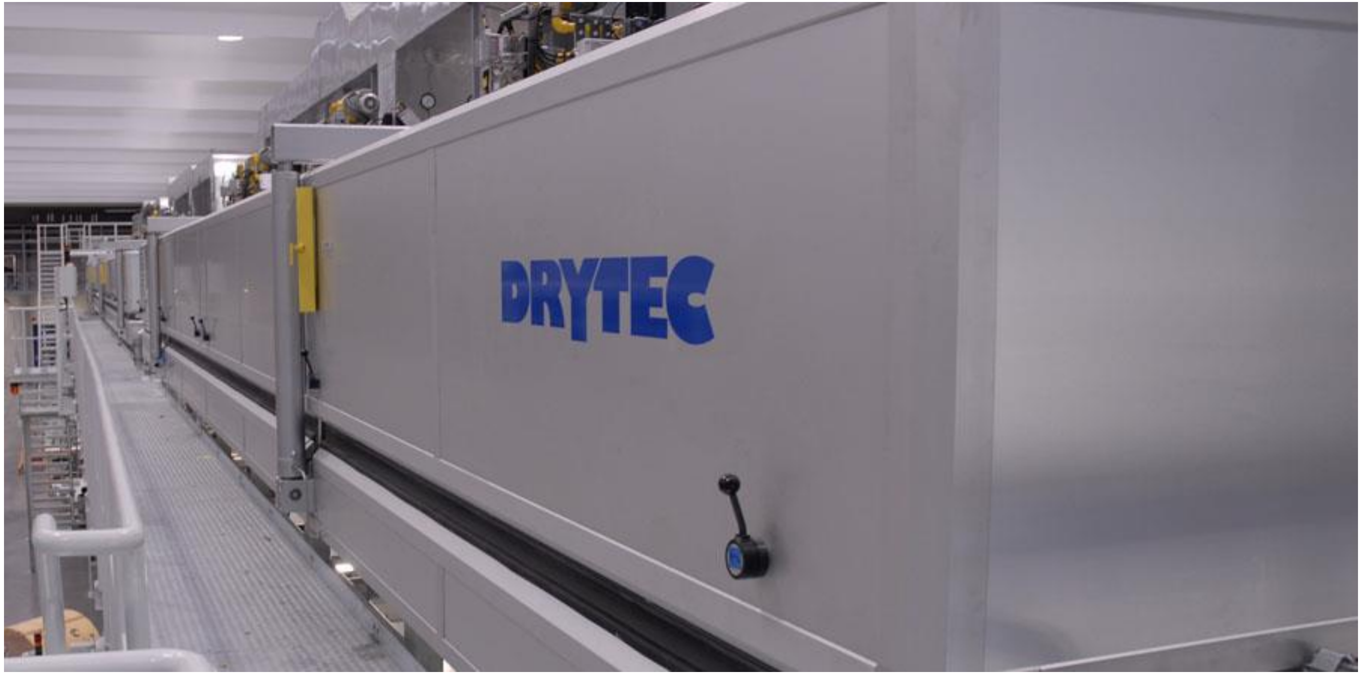
1. **„IN – OUT" mode** -> Operation where the drying air / gas will not be recirculated
   - ✓ Small machines and R&D lines
   - ✓ or high requirements to the drying air / gas (e.g. purity)

2. **Recirculating mode** -> Operation where the drying air / gas will be recirculated and only a necessary part of drying fluid will be purged
   - ✓ The ratio of exhaust / circulated volume shall be < 0.5
   - ✓ Coating / converting machines
   - ✓ Paper machines etc.

3. **„OVER PRESSURE" mode** -> Operation where the drying air / gas will be recirculated and a surplus fresh air / gas occur
   - ✓ Inert drying systems (at the inlet and outlet area of the drying system)

Dryer heating sources

- ✓ Gas
- ✓ Thermal oil
- ✓ Steam
- ✓ Electrical energy



Soucre: Drytec

Dryer heating sources

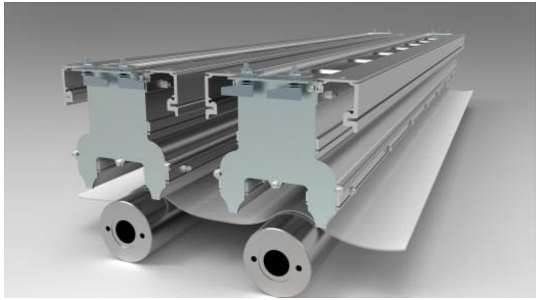
Wing shaped slot dryer

Wing shaped nozzle dryer with different nozzles

Simple slot dryer

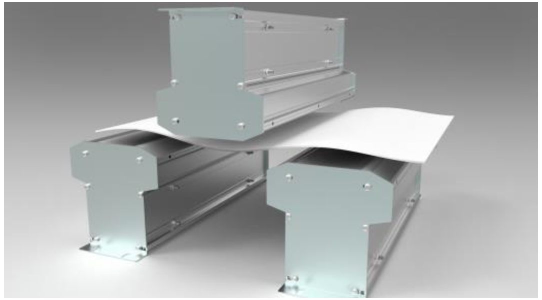
- ✓ Combined functions of heating and vapor transport
- ✓ Bulk heating by heat transfer from the surface
- ✓ Overheating easily avoided by limited air temperature

Nozzle shapes 1

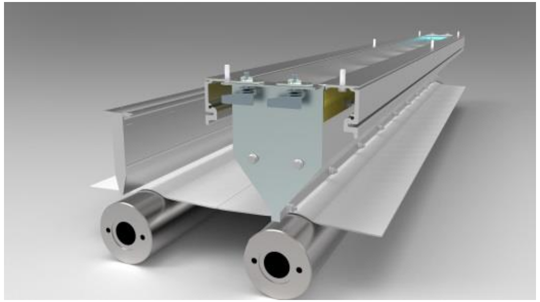


Impingement nozzles with two jets

Flotation nozzles with adjustable air direction



Flotation nozzles



Impingement nozzles with one jet

Flotation nozzles with Contec 3 roller nozzle

*) Contec 3 – Nozzles are placed directly above each other. The top nozzles have to be directly above the rollers which are placed in nozzles.

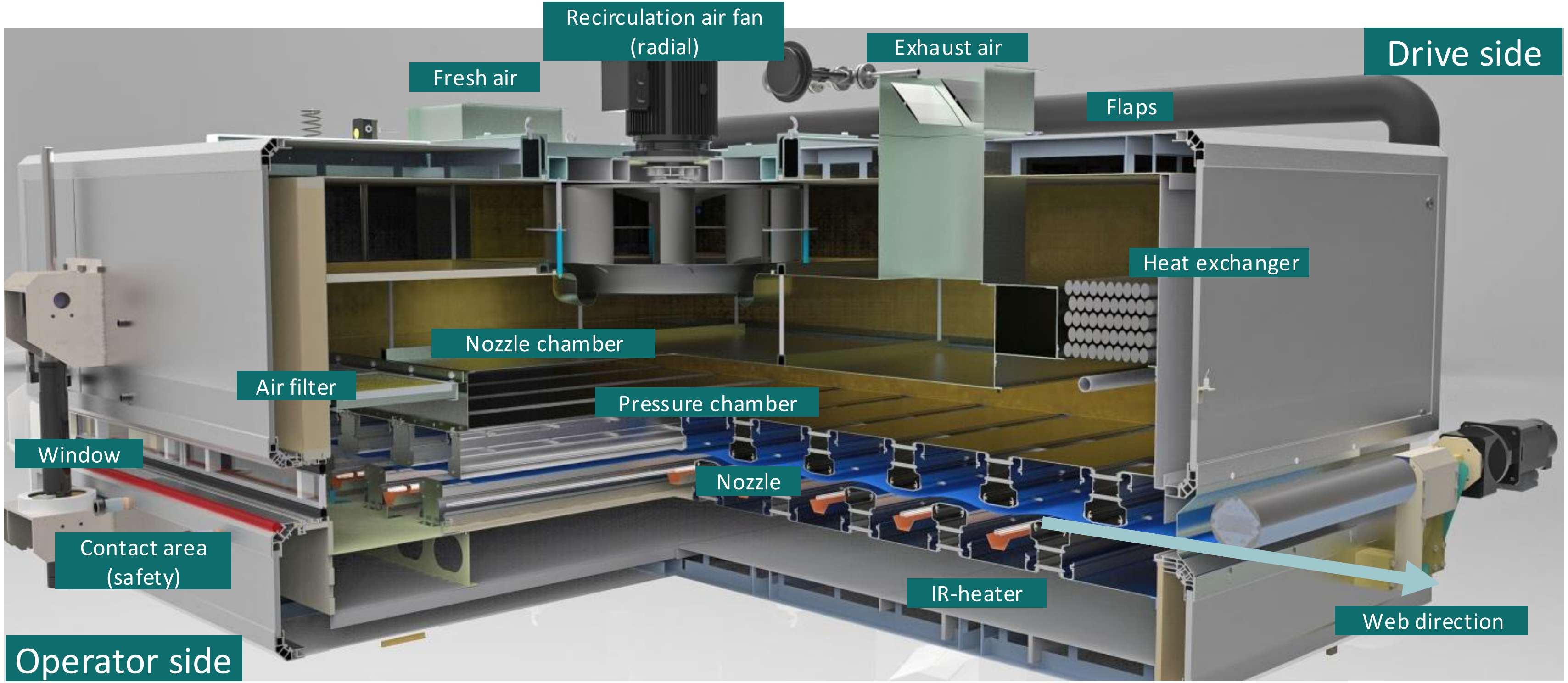
Nozzle shapes 2

Flotation nozzles with contec
1 roller nozzle

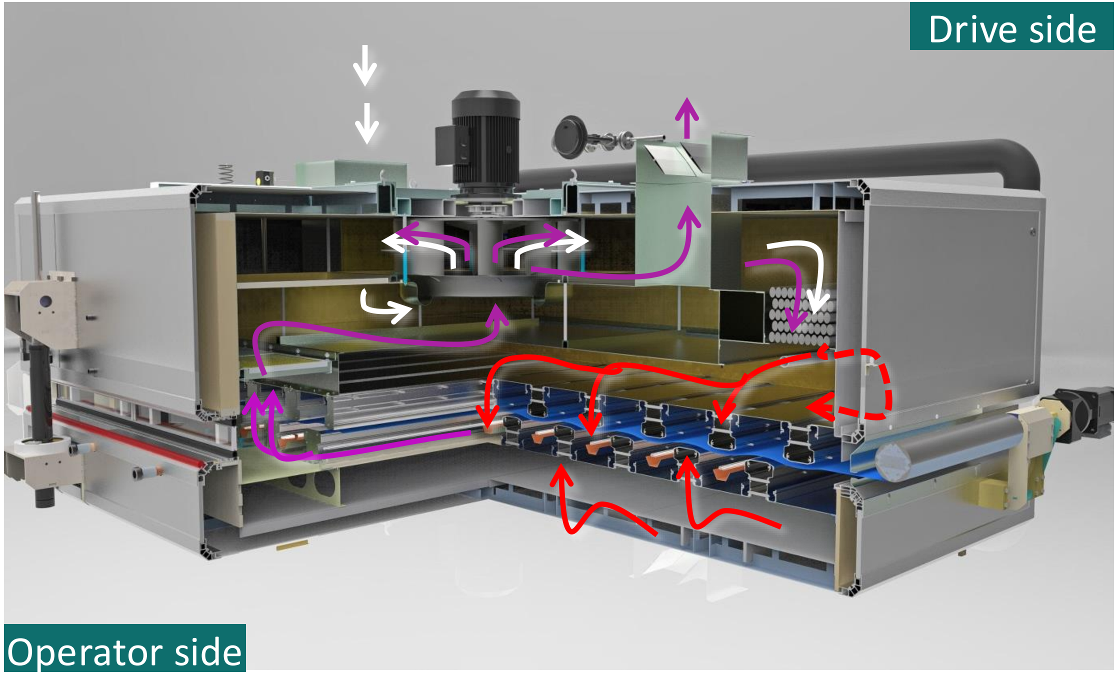
Flotation nozzles with contec
2 roller nozzle

Flotation nozzles with contec
3 roller nozzle

Drying topics – drying technologies: HighDry HD500



Drying topics – drying technologies: HighDry HD500



Air flow air inlet (cold)

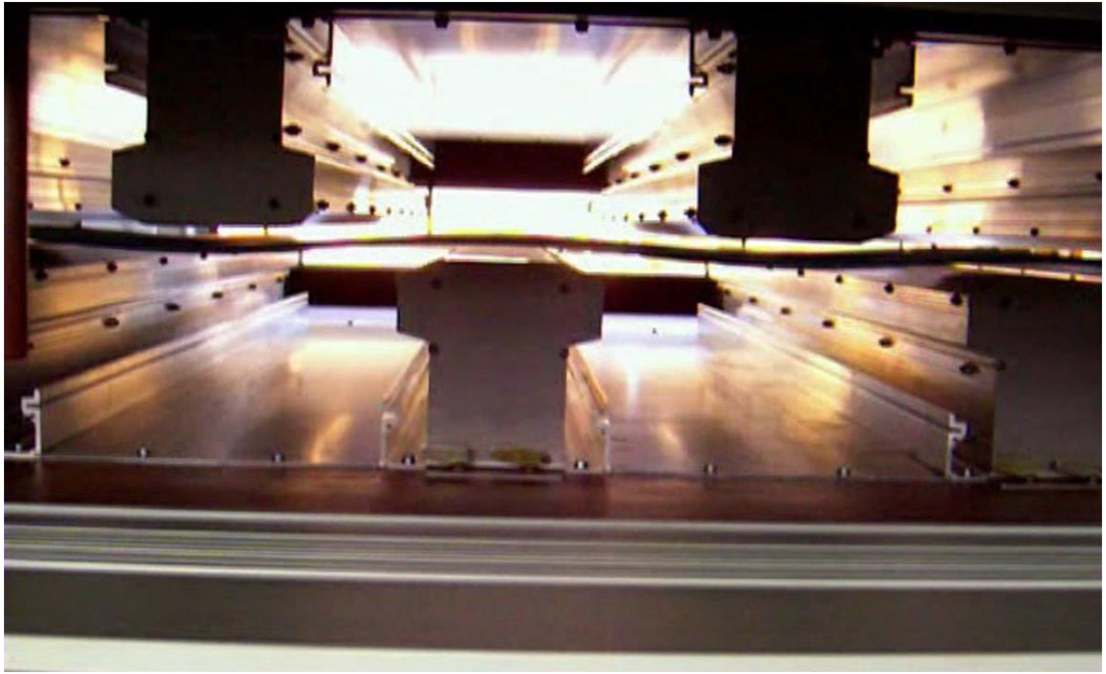
Air flow heated air (hot)

Air flow reverse

Clear arrows

Click „Air distribution“ to show air flow direction

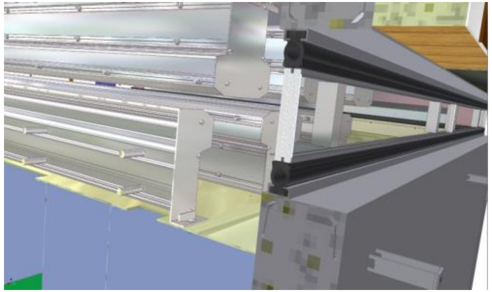
Drying topics – drying technologies: HighDry HD500



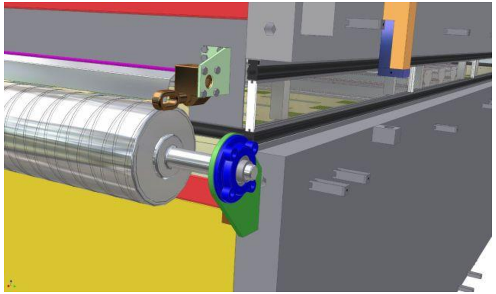
Web behaviour in a flowtation dryer

Click on the picture to show the video

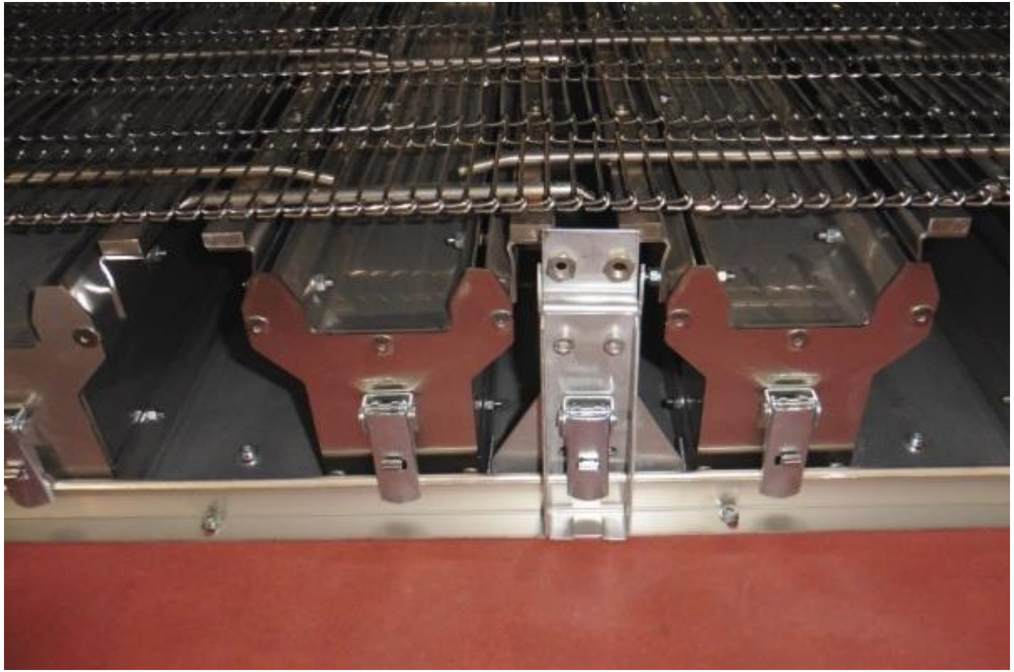
Dryer design – double glass windows



Along both sides of the dryer
for the observation of the web



Dryer design with transport system – metal grid



Dryer design with transport system – transport belt

Typical position of the dryer in the second level of a coating line

(N)IR technology – combined hot air / (N)IR dryer

5.

Summary

Comparison

Short wave NIR can be of great advantage, but only if applicable.

Applicability depends on coating liquid and substrate.

(The table focusses on applicable cases)

	Hot air dryer	Heated drum-based dryer	Infrared dryer	NIR drying technology	UV/EB curing
Drying time of physical drying	> 1.0–20.0 s	Depending on substrate thickness ~> 1.0 s	0.3–10.0 s	0.02–1.5 s	Not applied
Curing time of cross-linking section	5.0–30.0 s	3.0–15.0 s	1.0–10.0 s	0.1–2.0 s	0.1–2.0 s
Dynamic capability	Preheating and standby operation while web stop required	Preheating and standby operation while web stop required	Mostly no preheating required	Fully instantaneous start/stop capability	Depending on system, extreme dynamic, often preheating required
Max. possible production speed	Mostly only up to 600 m/min (1969 fpm)	Mostly <100 m/min (328 fpm)	Max. up to <1000 m/min (3281 fpm)	At present no limit up to >2000 m/min (6562 fpm)	Mostly only up to 600 m/min (1969 fpm)
Risk regarding thermal damage	High, depending on air temperature especially at fast web stop	High, depending on drum temperature	Lower, but given depending on heat due to mass of dryer design	Low, due to working principle and dryer design	Low, due to working principle
Applied for thermal sensitive substrates	Limited to low air temperature (<80 °C/ 176 °F) results in strong reduced drying performance	Limited to low drum temperature (<80 °C/ 176 °F) results in strong reduced drying performance	Limited to low drying power due to resulting thermal stress	Possible up to high production speed due to working principle and dryer design	Possible up to high production speed due to working principle an dryer design
Risk regarding penetration of the coating materials in open substrates	Cannot be avoided due to long drying time required	Cannot be avoided due to long drying time required	Can be reduced slightly, but not completely avoided	Can be avoided, due to extreme short drying time and high energy density	Can be avoided, due to extreme short drying time and high energy density
Consumption of consumable material	High, especially due to penetration in the substrate	High, especially due to penetration in the substrate	Lower, because of low penetration	Lower, because of mostly avoided penetration in the substrate	Lower, because of mostly avoided penetration in the substrate

Soucre: courtesy Adphos

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