Technology development and manufacturing for fuel cells and electrolyzers

Coatema

09/01/25

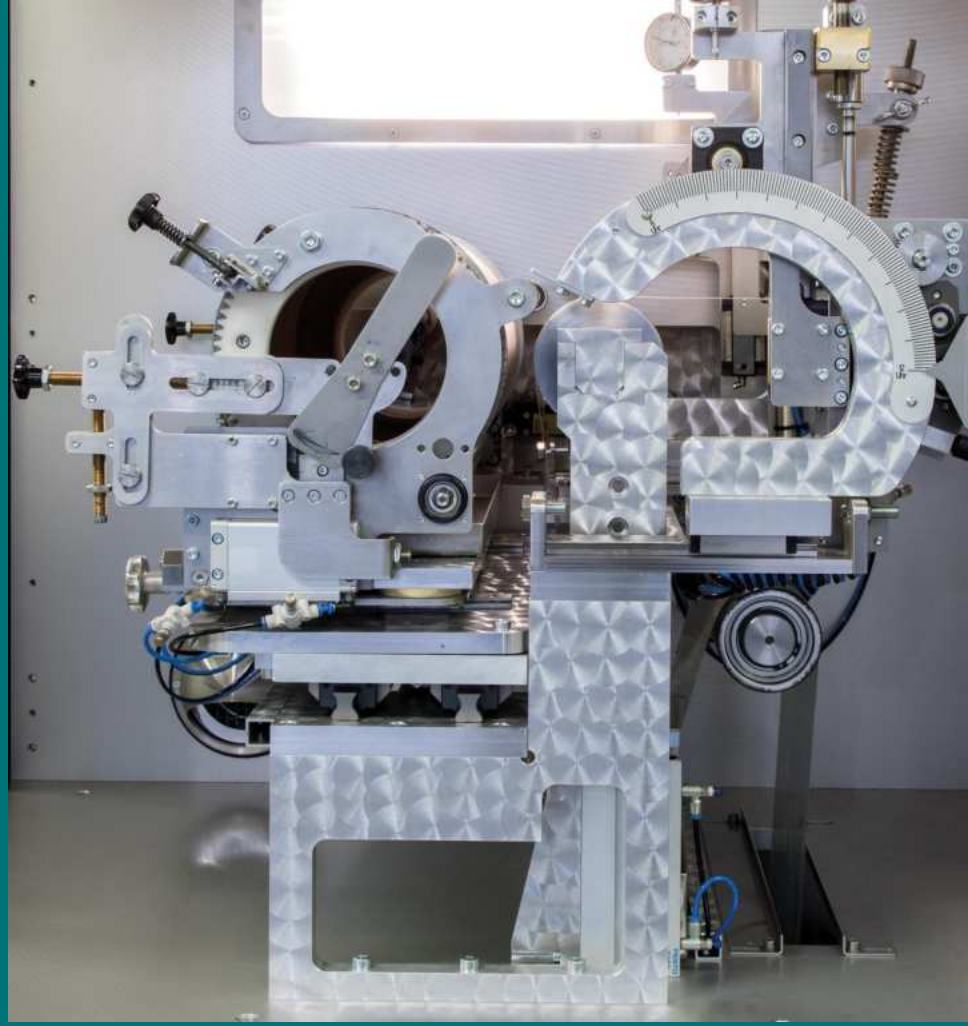
MEMBER OF ATH

Agenda

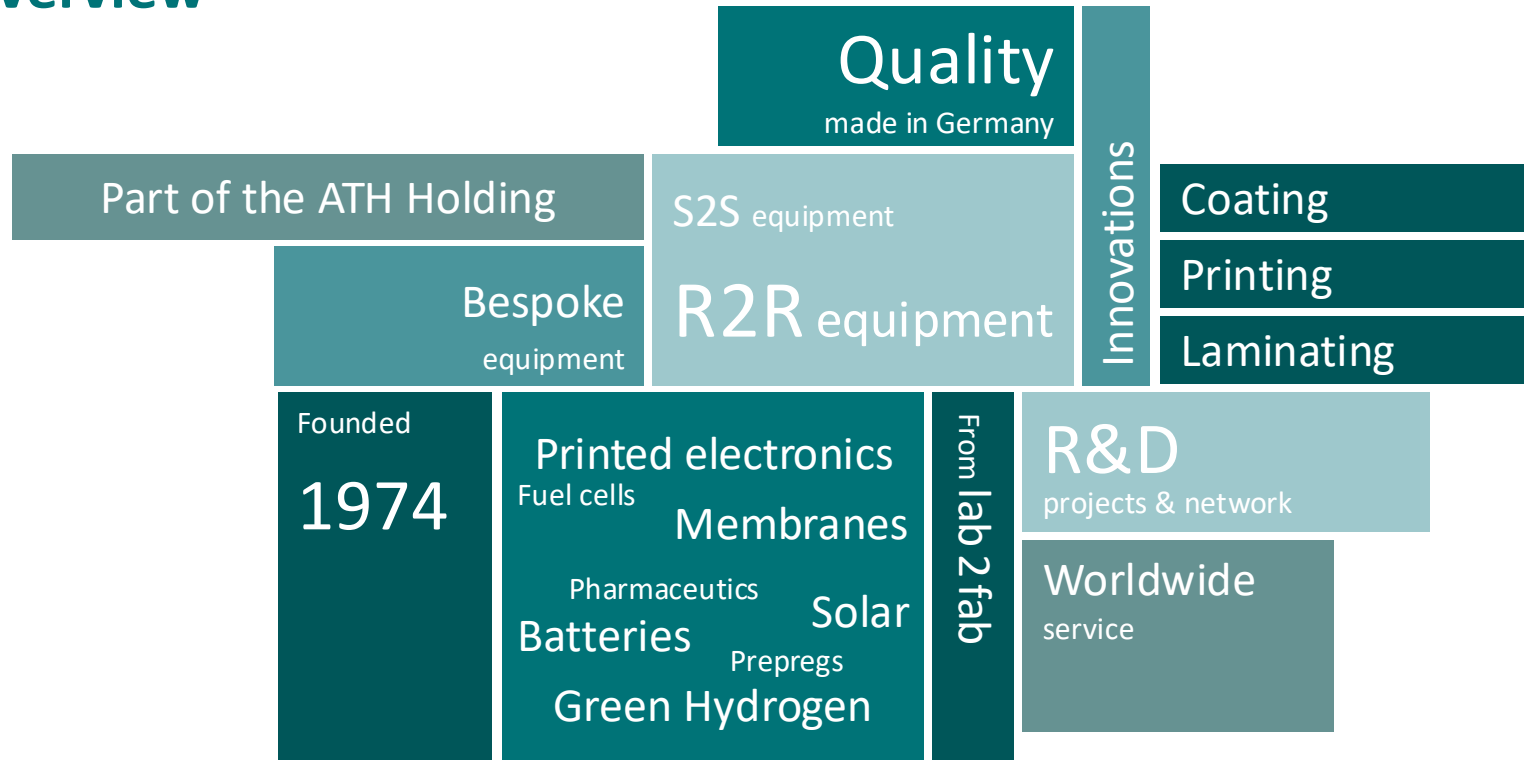
1. Introduction
2. Today‘s equipment
3. Coating systems
4. Slot die for fuel cells
5. Digital application system
6. Drying technologies
7. Simulation
8. Summary

1.

Introduction



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

Our markets – Coatema focus areas

- Green Hydrogen
- Fuel cells
- Batteries
- Solar

- Sustainability
- Digital fabrication
- Printed electronics
- The next thing

Coatema equipment platform strategy for lab2fab

Lab

- ✓ State-of-the-art research and development equipment
- ✓ Sheet-to-sheet to roll-to-roll systems

Pilot Production

- ✓ Proven electrolyzer and fuel cell coating and laminating equipment
- ✓ Highest-quality pilot product lines enable stable pilot production and reduce cost
- ✓ Scaling laboratory equipment to enable pilot production

Production

- ✓ Full-scale production line for electolyzers
- ✓ Elevating our in-depth roll-to-roll equipment to fully scale production and further reduce adoption cost

R&D centre USP

Process development
- ✓ Feasibility study
- ✓ Ink – process study
- ✓ Process analysis
- ✓ Slot die coating simulations
- ✓ Proof of concept
- ✓ Small scale prototype

Test production
- ✓ Prototyping
- ✓ Near to market testing
- ✓ TRL evaluation
- ✓ Training of staff

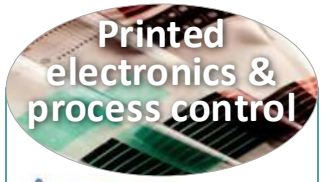
Education
- ✓ Coating conference
- ✓ Partner trainings
- ✓ Education of students
- ✓ Workforce training

Development of custom-made design for equipment
- ✓ Prototyping
- ✓ Proof of concept

Public funded research projects know-how
- ✓ German funded
- ✓ Horizon 2020
- ✓ Global 2+2 projects
- ✓ B2B projects

R&D customers

R&D projects overview 2022 – 2024



REAL NANO

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

NOUVEAU PROJECT

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

ENP

Development of near-field electro hydrodynamic nanowire printing

IDEEL

Implementation of laser drying processes for lithium-ion battery production

SOLiD

R2R process optimization for solid state batteries

pepLAT

Plasmonically enhanced photocatalysis for wastewater treatment

RetroWin

R2R Process and machinery development for retrofit window films for lower production costs

WATER PROOF

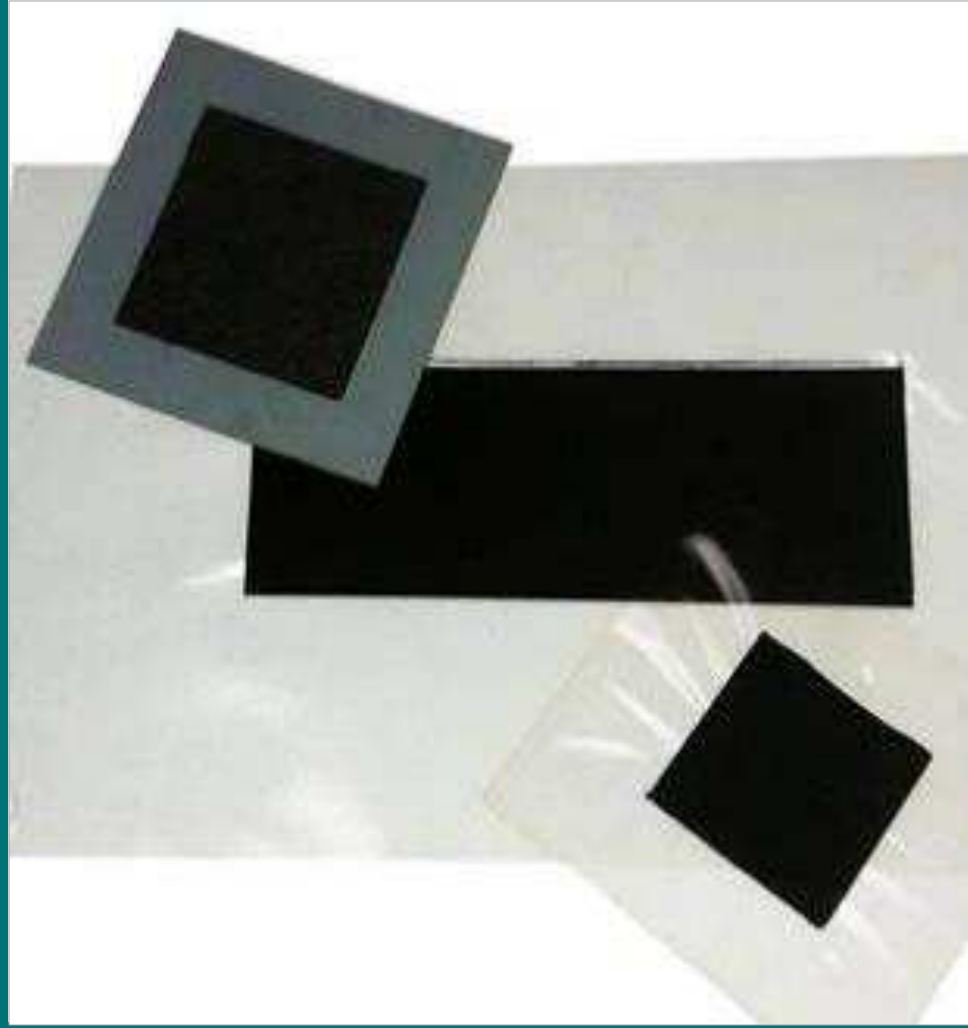
The WaterProof project aims at developing an electrochemical process that converts CO_2 emission

FLEX FUNCTION 2 SUSTAIN

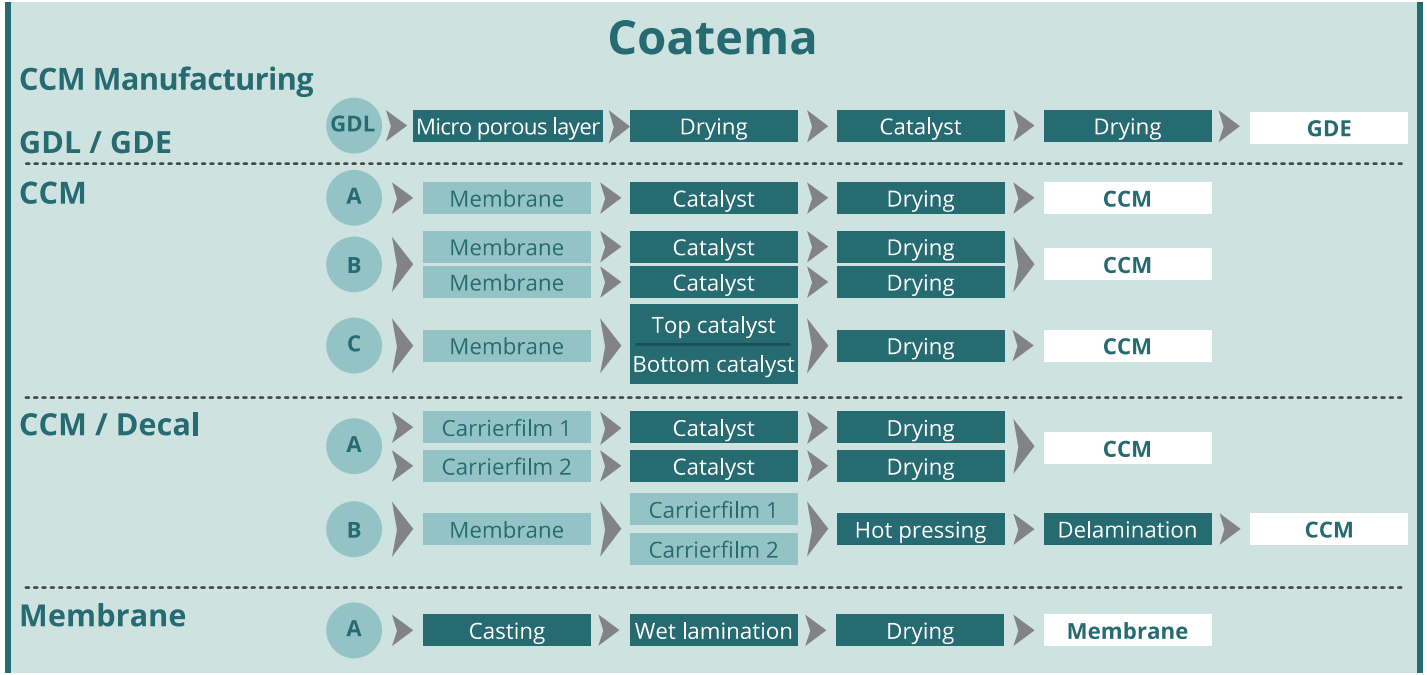
Creating an open-innovation testbed for sustainable packaging

2.

Today‘s equipment for todays fuel cells/electrolyzers



Reference equipment for electrolyzer Coatema



Legend:

- Input
- Process
- Output

CCM = Catalyst Coated Membrane

GDL = Gas Diffusion Layer

GDE = Gas Diffusion Electrode

MEA = Membrane Electrode Assembly

S2S

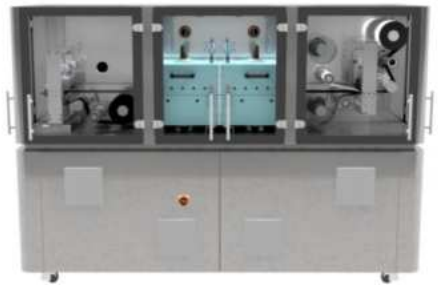
Test Solution

Easycoater

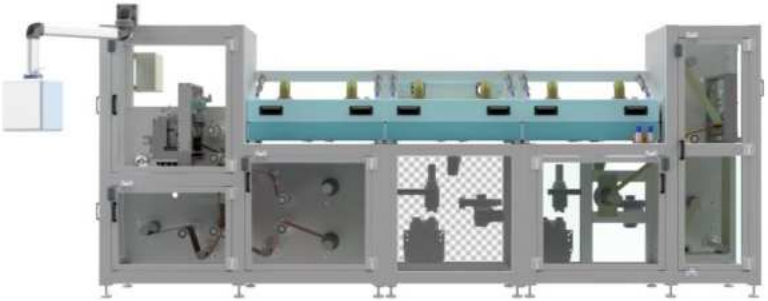
Easycoater Evolution

Ink testing	First sample product	First pilot as S2S

Roll-to-Roll (R2R) lab systems



Test Solution R2R



Basecoater R2R

Smartcoater R2R

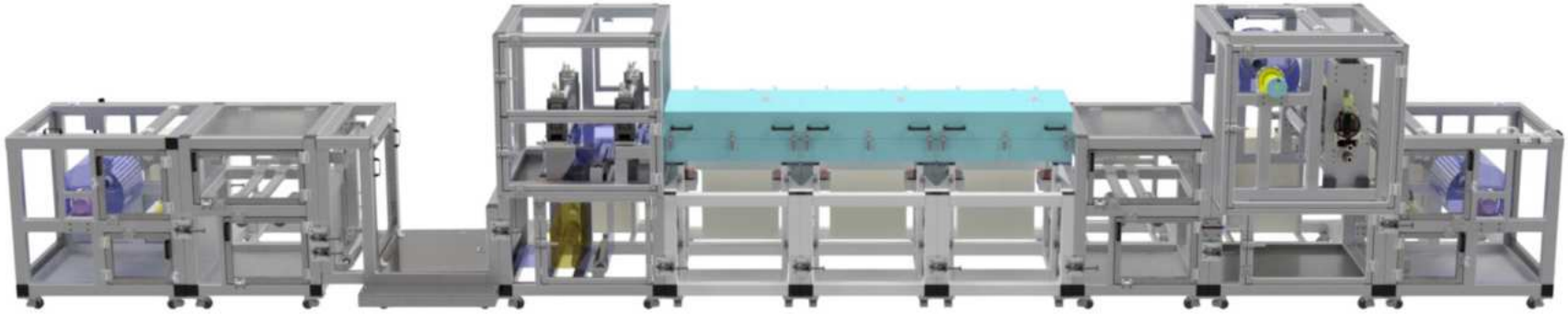
Verticoater R2R

The Smartcoater

The Smartcoater

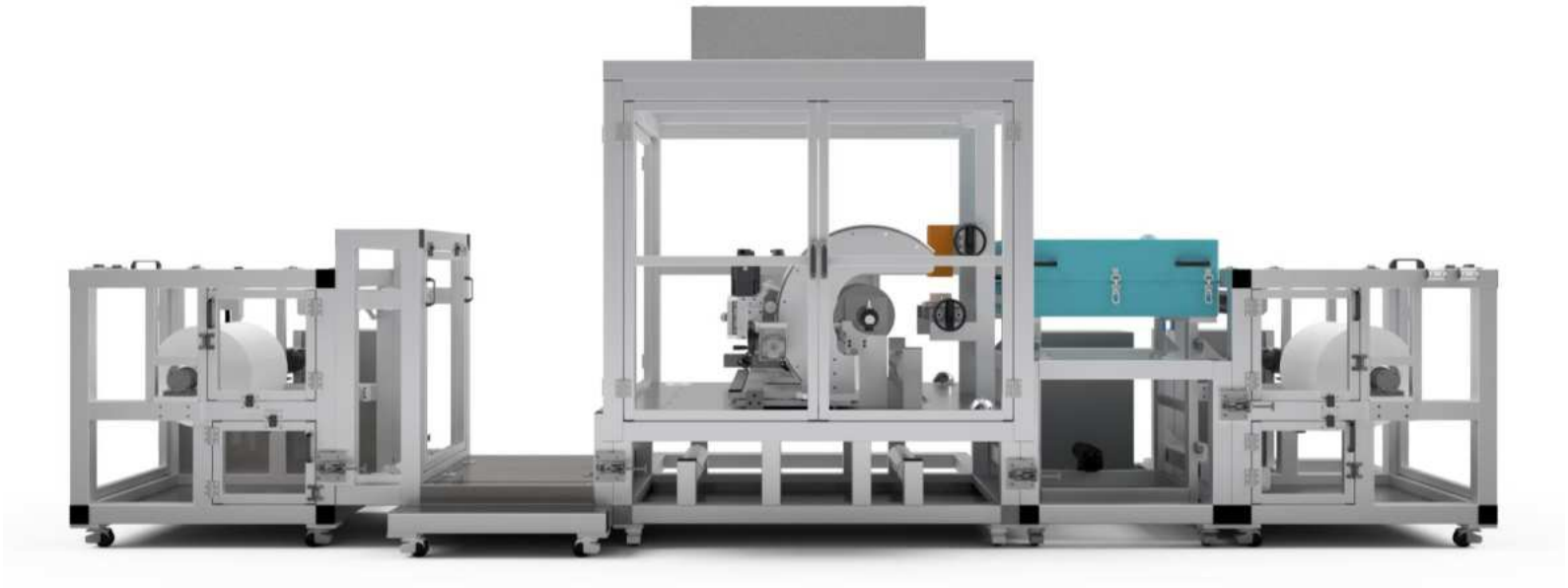
Roll-to-Roll (R2R) pilot

Basecoater Pilot R2R

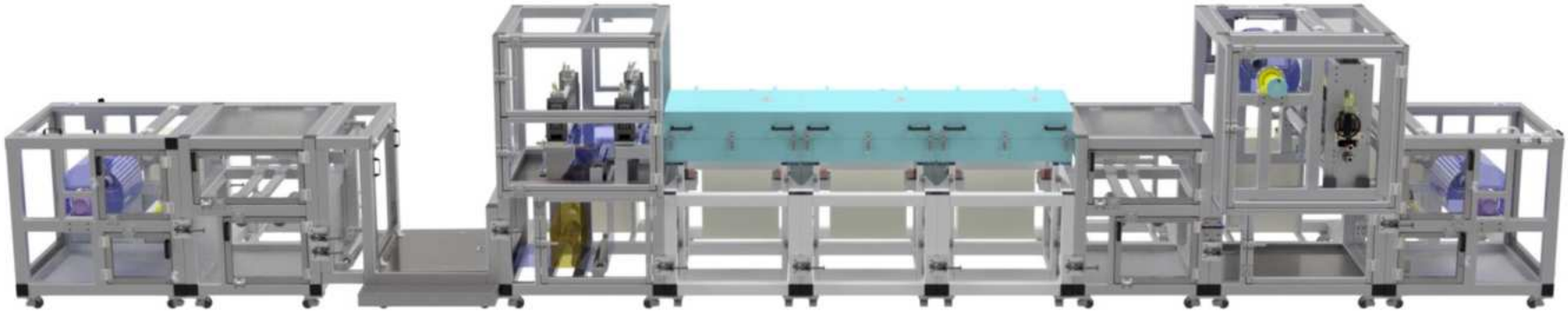


Click&Coat™ R2R

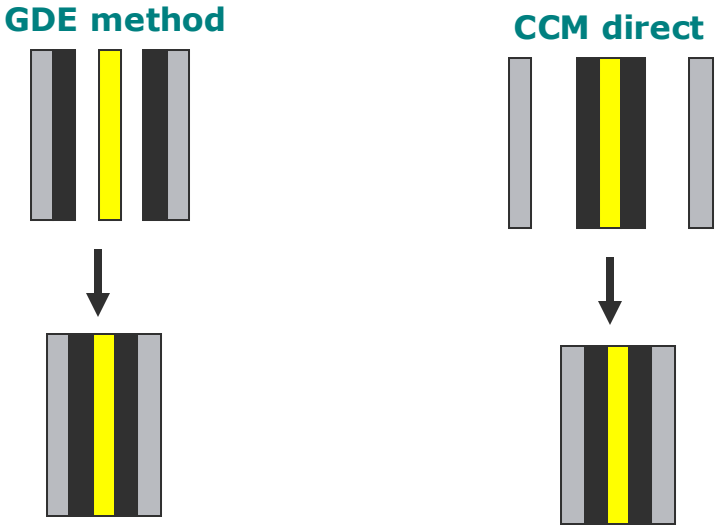
The Click&Coat™



The Click&Coat™



GDE and CCM coating lines



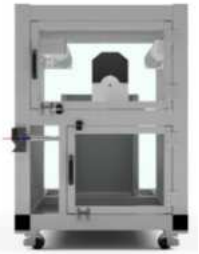
The Click&Coat™

The Click&Coat™

Specific equipment in Click&Coat™ layout

Click&Coat™ your own ideas

Winder



Corona

Podestral

Coating

Printing

Dryer

Laminator

Rewinder

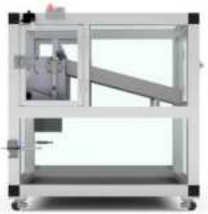
Chemical treatment bath

Inert Coating and laminating

Registration control

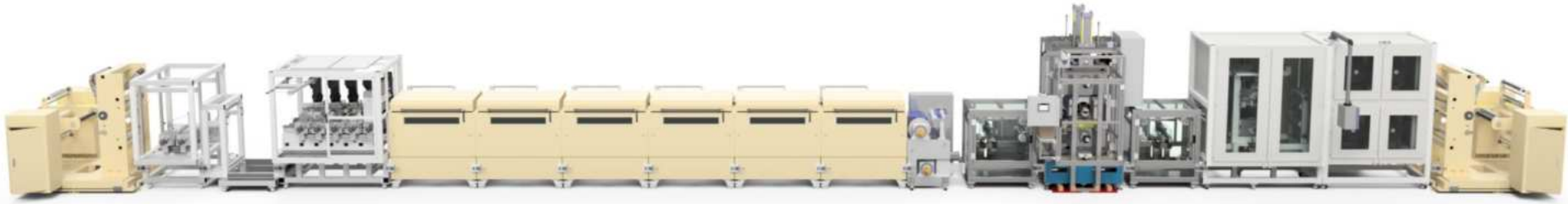
Turning device

Lamination



Cutting

The Click&Coat™ in production scale in the R&D centre



The Click&Coat™ in production scale

The Click&Coat™ in production scale

- ✓ Unwinder
- ✓ Lamination
- ✓ Delamination
- ✓ EPC
- ✓ Web cleaning
- ✓ Corona

- ✓ Thickness measurment Substrate

- ✓ Podestral

- ✓ Interchangable
- ✓ Coating module
- ✓ EPC
- ✓ Register
- ✓ Coating control

- ✓ Thickness measurment
- ✓ Wet coating

- ✓ Flotation dryer
- ✓ NIR
- ✓ IR
- ✓ UV
- ✓ Laser
- ✓ Humidity

- ✓ Optical
- ✓ Surface control
- ✓ Cooling table

- ✓ Lamination
- ✓ Thickness measurment
- ✓ Dry coating

- ✓ XRF - measurment
- ✓ Platinium loading

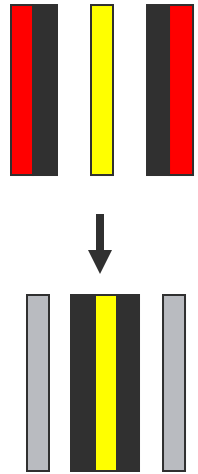
- ✓ Thickness measurment
- ✓ Substrate

The Click&Coat™ in production scale

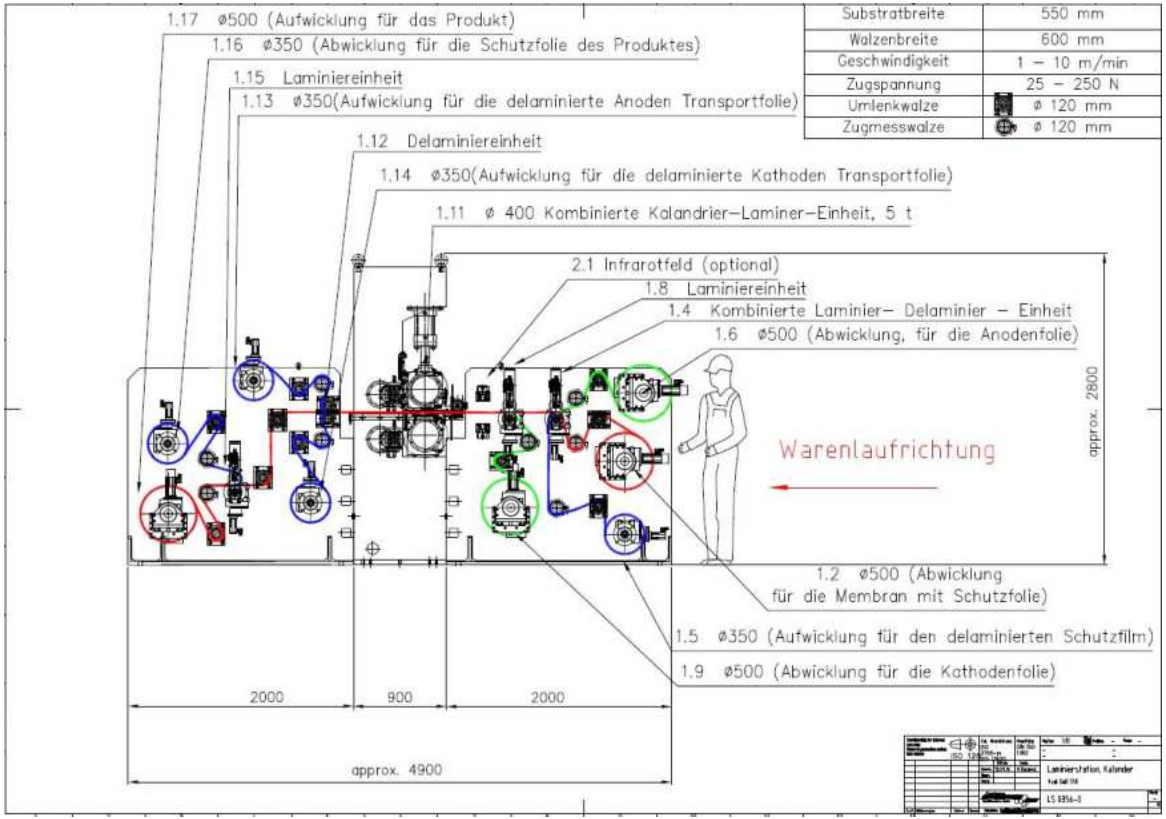
The Click&Coat™ in production scale

Indirect CCM (Decal) Method

CCM indirect

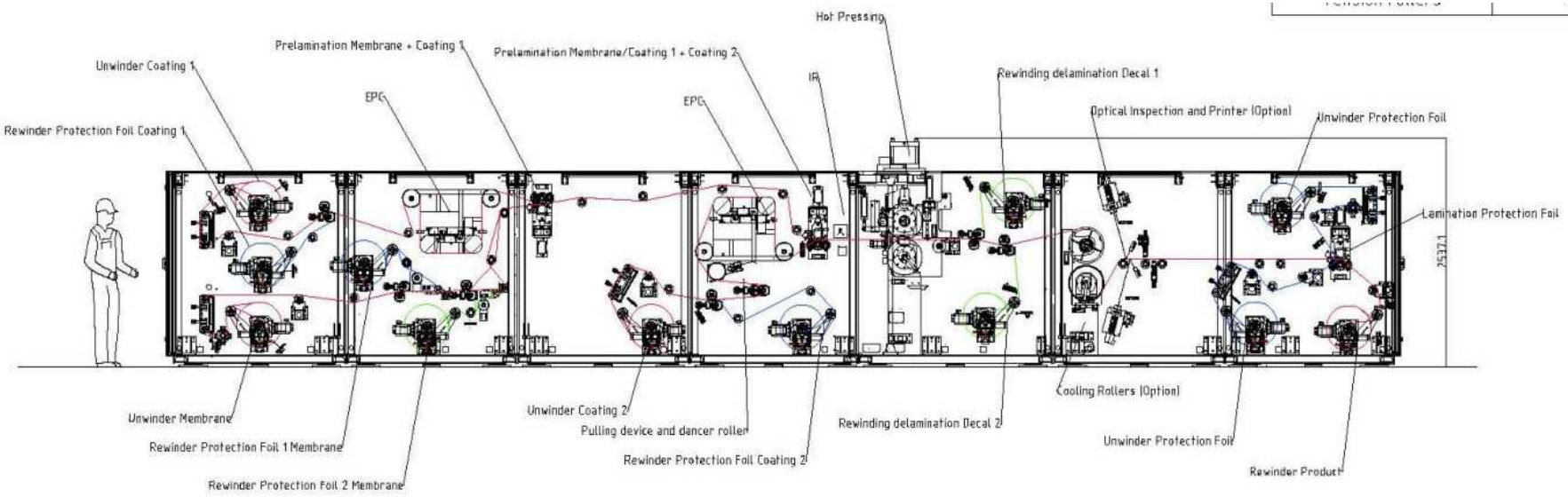


Decal 3rd Generation



Hot pressing

Decal 3rd Generation



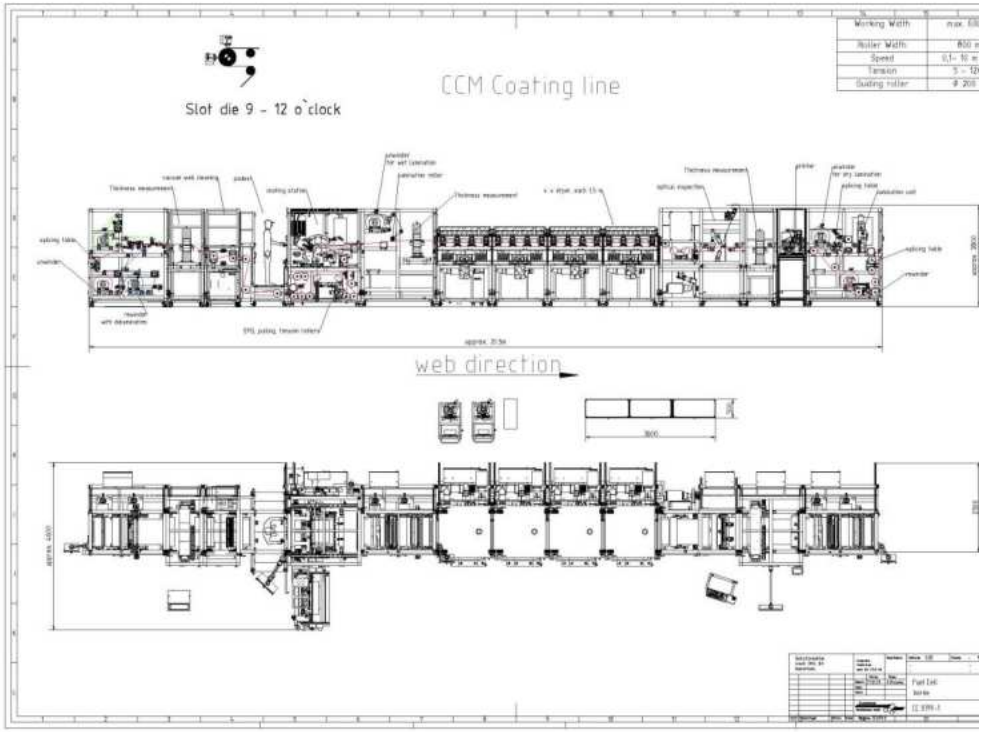
Membrane casting and reinforced membrane (wet lamination)

Membrane (Casting)

Reinforced Membrane (wet lamination)

Membrane casting

Membrane casting



Production line for fuel cells – 1000 mm working width

3.

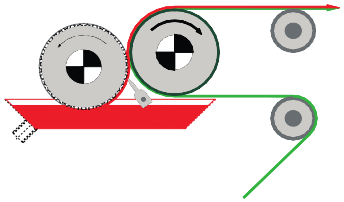
Coating systems

Coating parameters

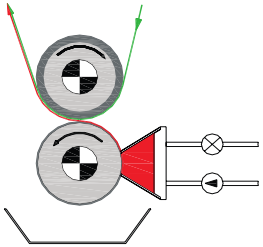
Coating chemistry	Coating processes	Process control	Drying
✓ Rheology ✓ Viscosity ✓ Viscoelasticity ✓ Type of solvents ✓ Solid content ✓ Van der Waals force ✓ Sheer ratio ✓ Adhesion/Cohesion	✓ Coating systems ✓ Single or multilayer coatings ✓ Direct coatings ✓ Transfer (indirect) coatings ✓ Substrate 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

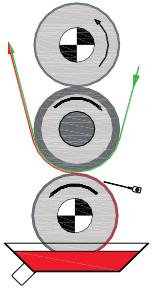
Printing systems



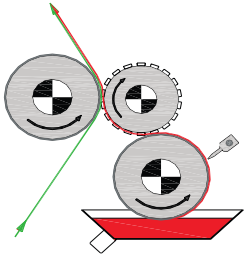
Engraved roller system



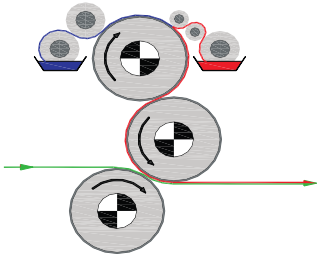
Gravure roller system



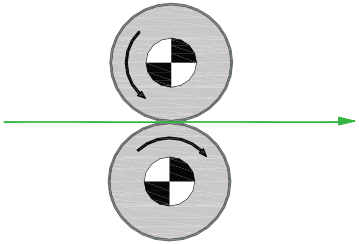
Gravure indirect system



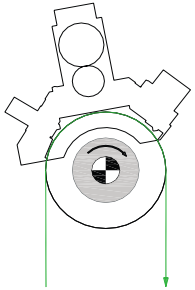
Flexography system



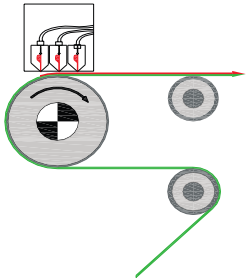
Offset lithography system



Hot embossing system

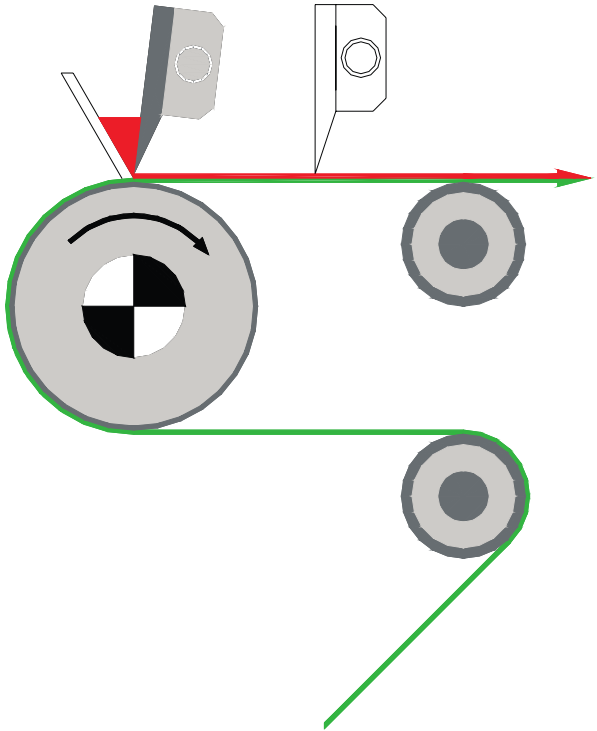


Nanoimprint system



Inkjet system

Knife coating



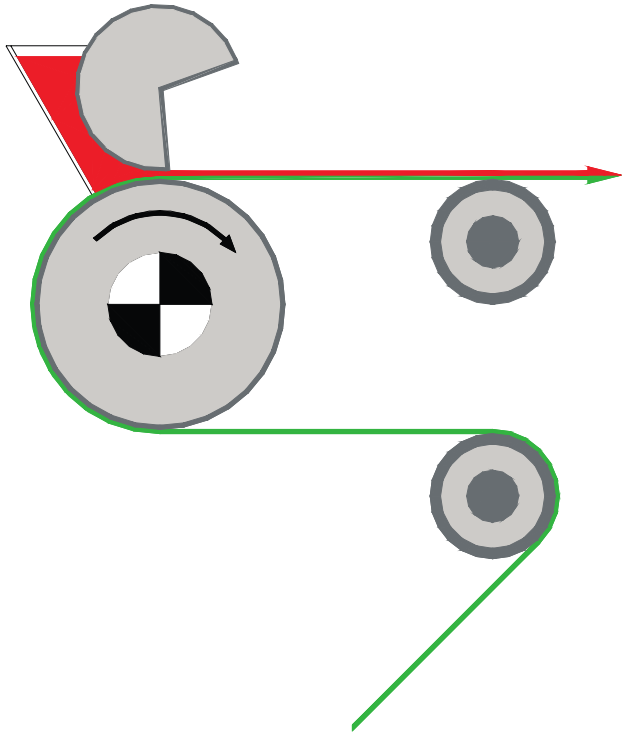
Variation of the coating weight

- ✓ Roller knife
  10 – 1.250 g/m²
- ✓ Air knife 5 – 6 to 60 g/m²

Range of viscosity

- ✓ Paste (1000)
  100 – 50 000 mPas
- ✓ Foam
  10 000 – 25 000 mPas
- ✓ Air knife
  5 – 10 000 mPas

Commabar coating



Variation of the coating weight

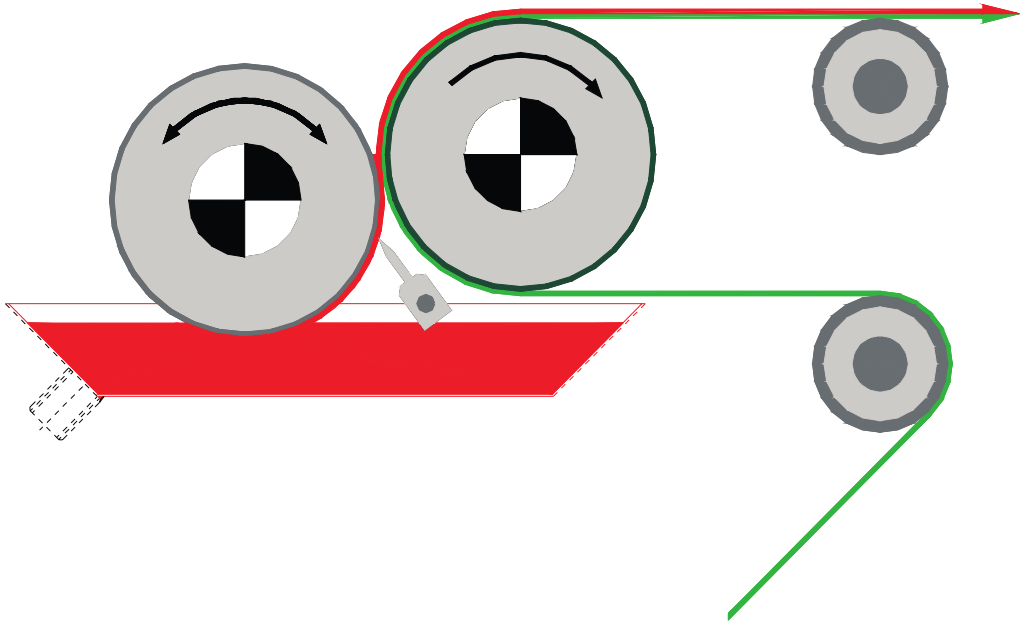
✓ Air knife
5 – 6 to 1.250 g/m²

Range of viscosity

✓ Paste
5 – 6 to 60 g/m²

✓ Foam
10 000 – 25 000 mPas

Gravur coating



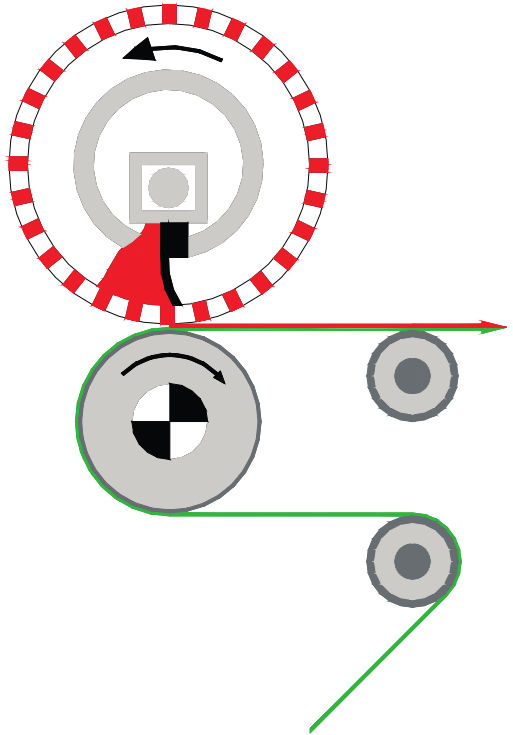
Variation of the coating weight

✓ 2 – 200 g/m²

Range of viscosity

✓ 1 – 15 000 mPas

Rotary screen coating



Variation of the coating weight

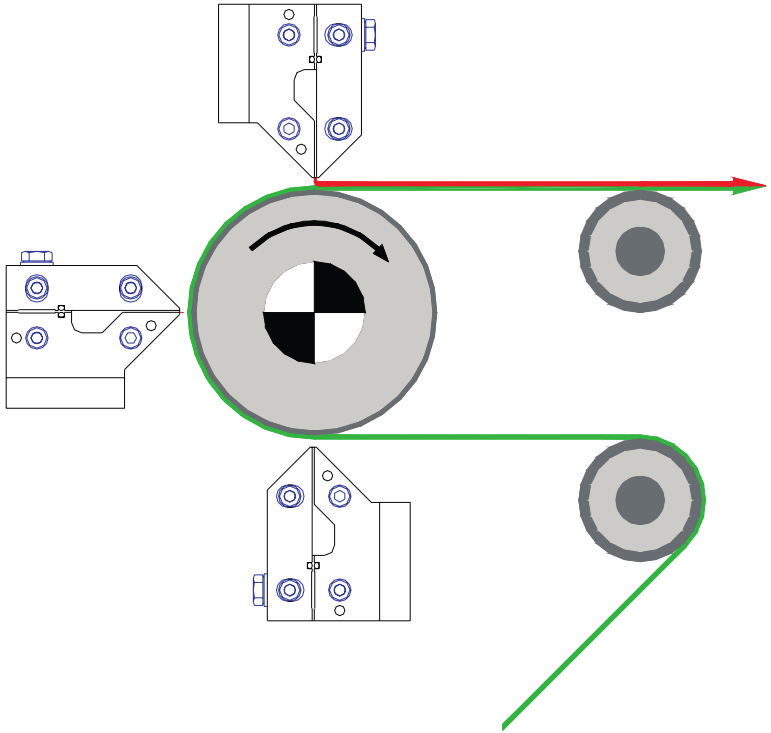
✓ 10 – 300 g/m2

Range of viscosity

✓ Paste
10 000 – 80 000 mPas

✓ Paste
10 000 – 25 000 mPas

Slot die coating



Variation of the coating weight

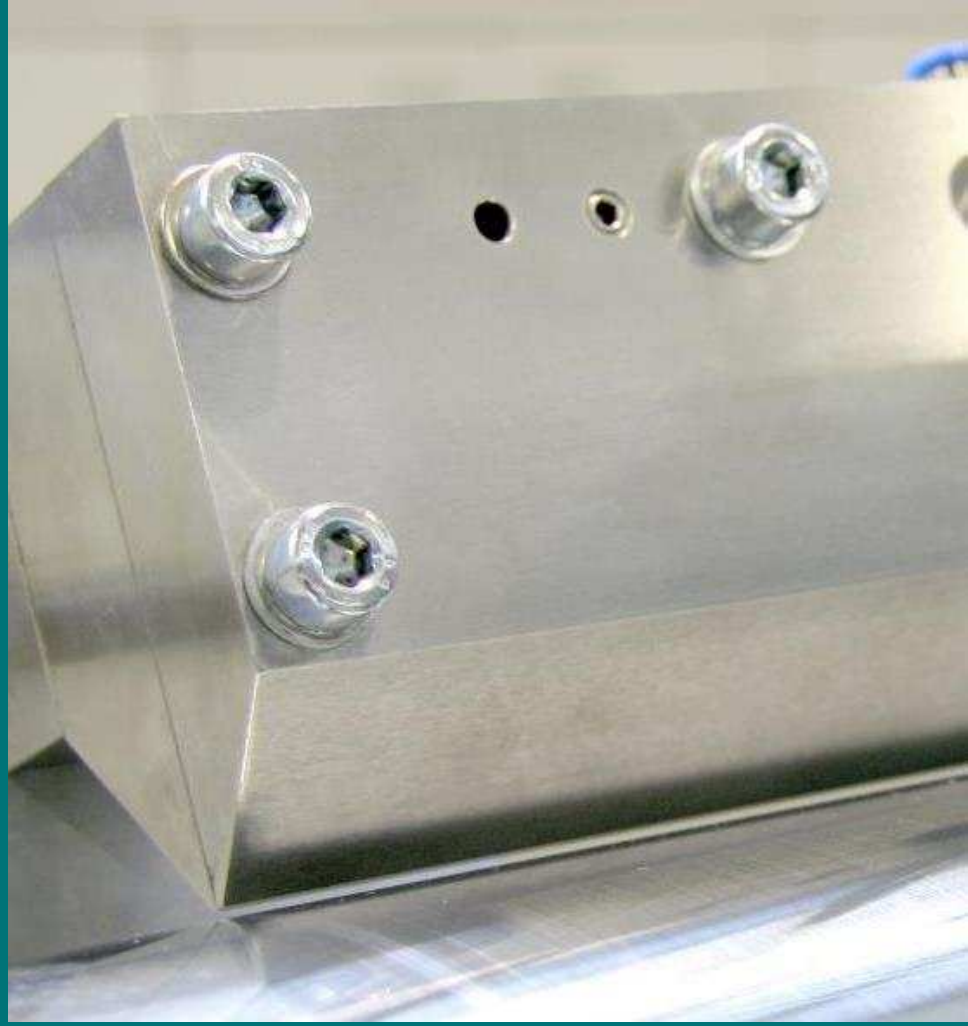
✓ 1 – 200 g/m²

Range of viscosity

✓ 1 – 30 000 mPas

4.

Slot die coating for fuel cells



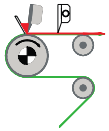
Basic principle

Coating parameters

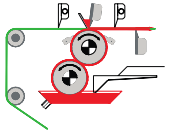
Ink properties	Coating processes	Process control	Drying
✓ Rheology	✓ Coating systems	✓ Process layout	✓ Convection drying
✓ Viscosity	✓ Single or multilayer coatings	✓ Tension control system	✓ Contact drying
✓ Viscoelasticity	✓ Direct coatings	✓ Material guiding system	✓ Infrared drying
✓ Type of solvents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

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

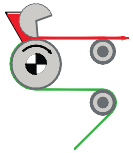
Coating systems



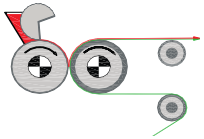
Knife system



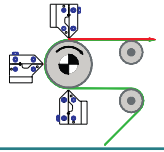
Double side coating system



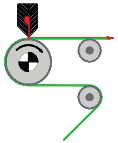
Commabar system



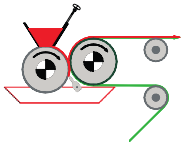
Reverse commabar system



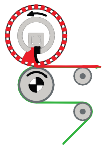
Slot die system



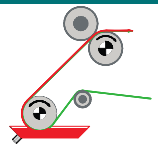
Curtain coating system



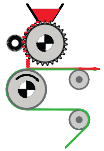
Case knife system



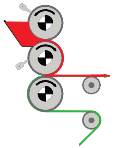
Rotary screen system



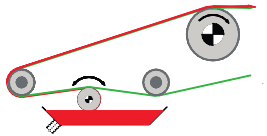
Dipping system (Foulard)



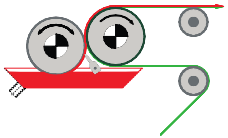
Powder scattering system



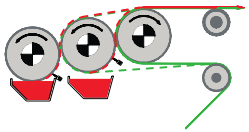
Reverse roll coating system



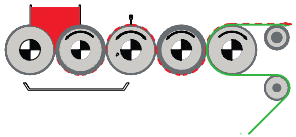
Micro roller coating system



2-roller coating system

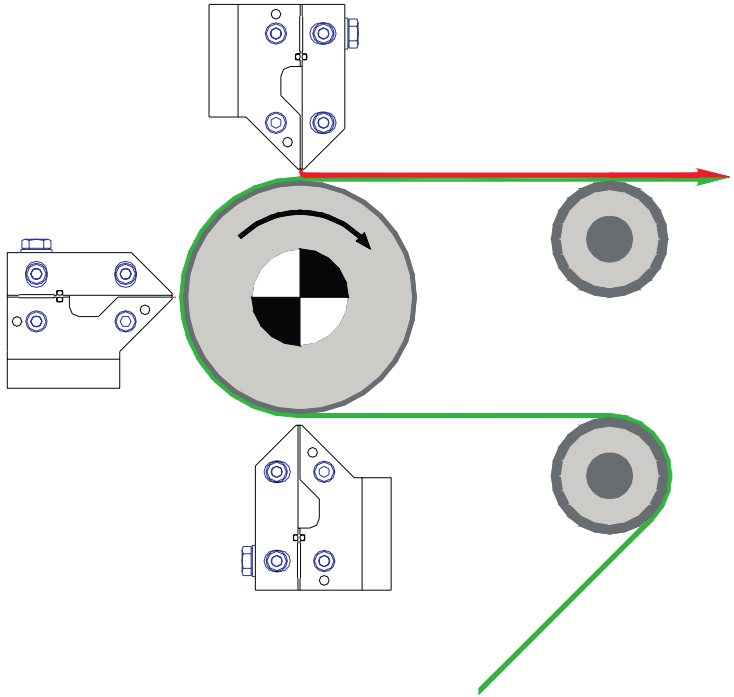


3-roller combi coating system



5-roller coating system

Basics of slot die coating – range of parameters



Coating speed
✓ 0.1 – >1000 m/min

Ink viscosity
✓ 1 – 300 000 mPas

Layer thickness (dry)
✓ 0.1 – >200 µm

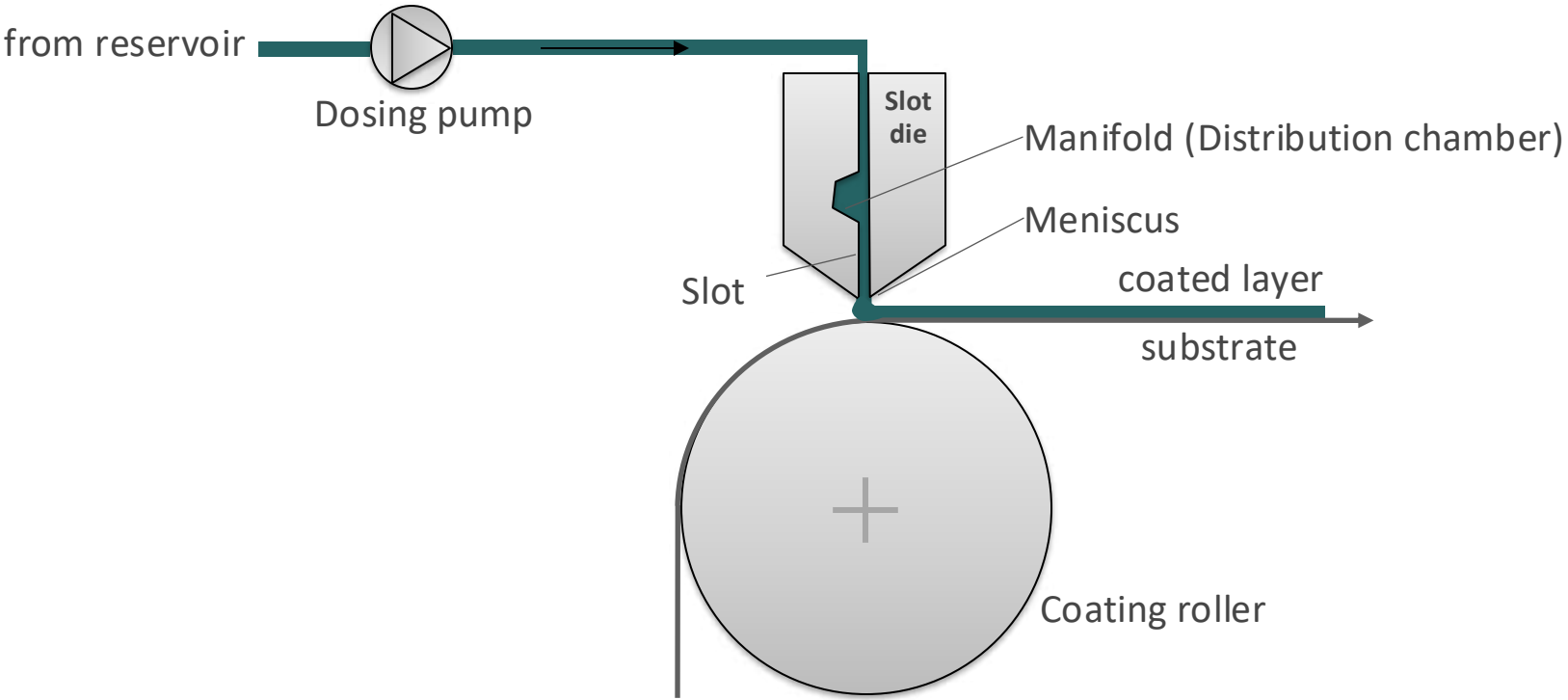
Coating accuracy
✓ <1% (2 – 5%)

Coating width
✓ up to approx. 3 m

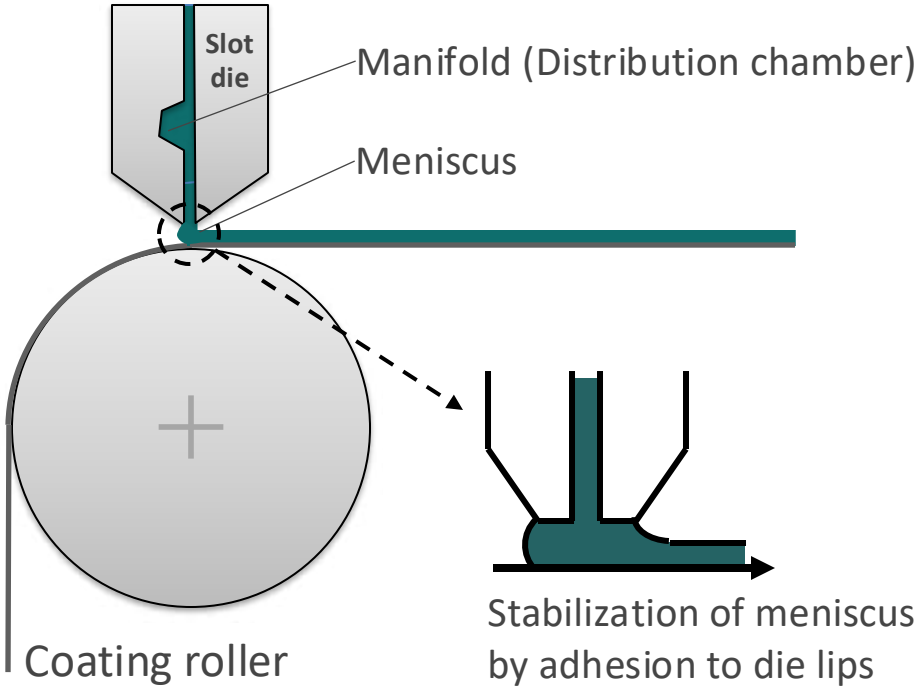
Basic principle

Basic principle

Basic principle



Bead mode



- ✓ Meniscus is formed between die lips and substrate
- ✓ Adhesive stabilization of meniscus by die lips
- ✓ Very low minimum flow rate possible
- ✓ For a stable process the range of rheological parameters is limited
- ✓ Preferrably for low coating speed

Theoretical background – „Basic“ fluid dynamics for advances geometries

$$\oint \rho v dA = 0$$

Continuity equation (conservation of mass)

Any flow of liquids is described by a set of differential equations:

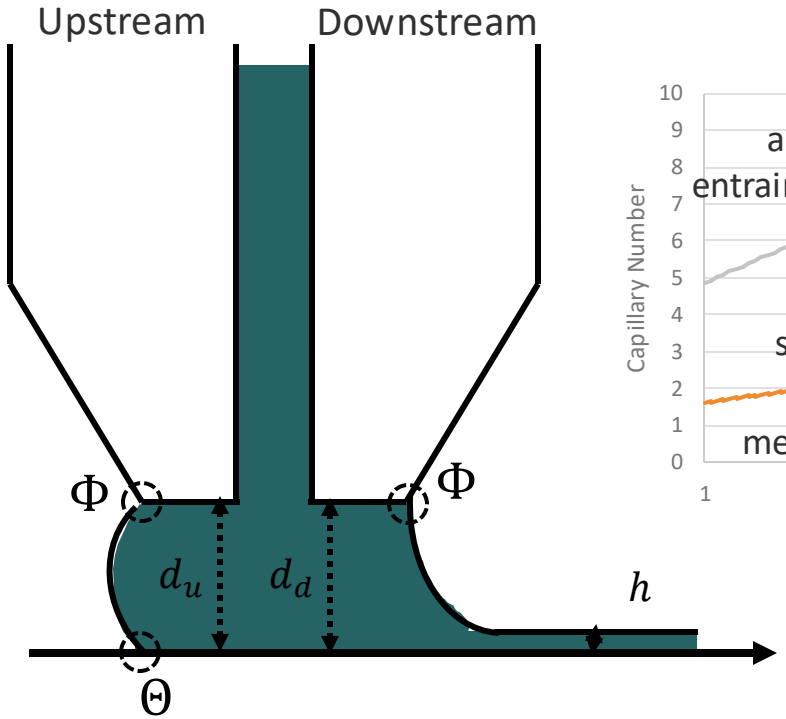
To describe the meniscus flow of a slot die means, to solve these differential equations for given boundary conditions.

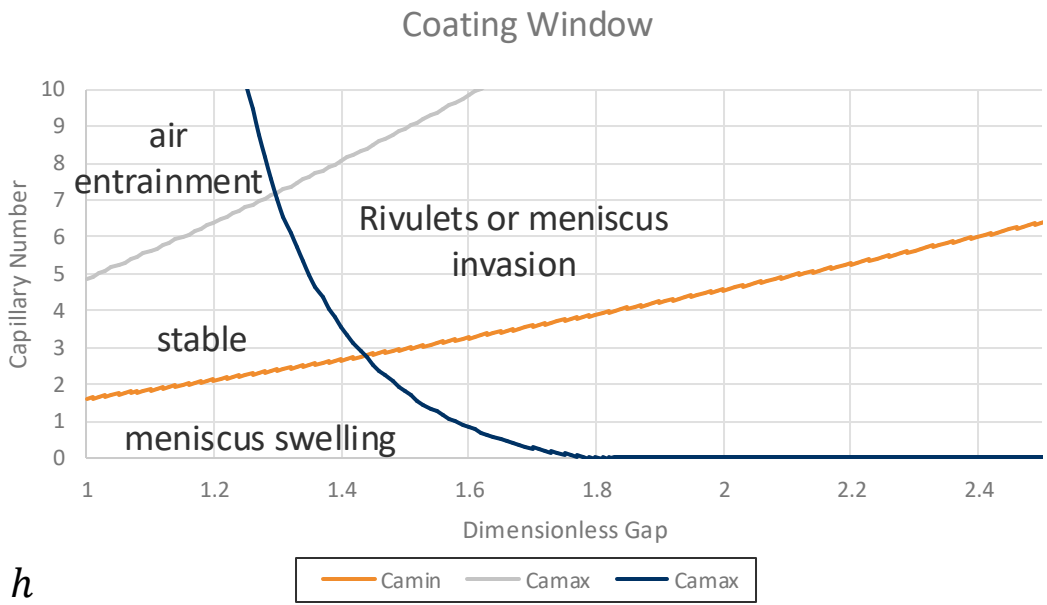
Can be done by appropriate computer programs.

$$\frac{\partial v}{\partial t} + (v\nabla)\,\mathrm{v} = \frac{(-\nabla p + \eta \Delta v + f)}{\rho}$$

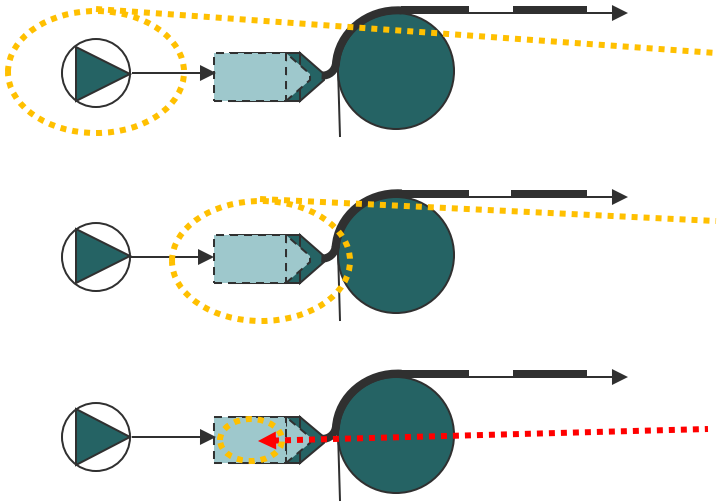
Navier-Stokes-equations (equations of motion for incompressible fluids, ρ = const)
Δ,∇= differential operators

Calculation of the meniscus stability





Standard techniques for intermittent coating



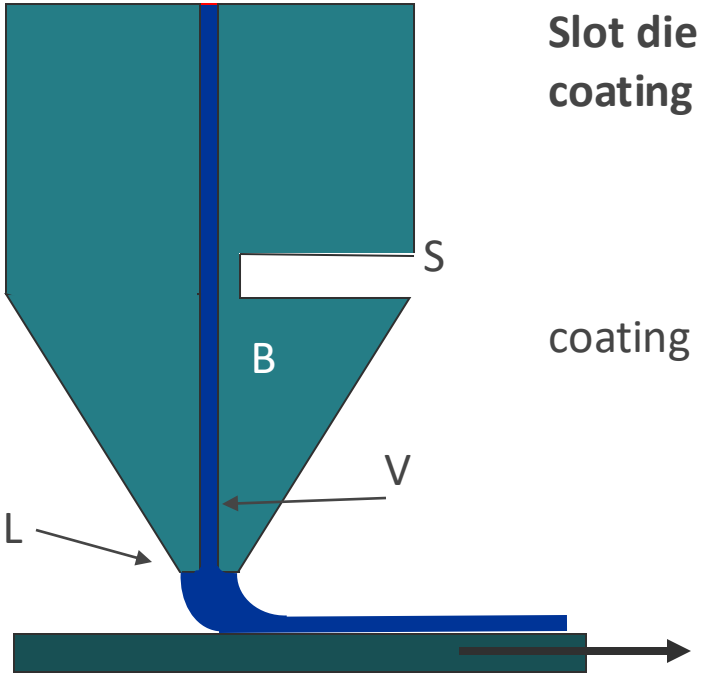
Pump:
stop – reverse – restart

Slot die body:
move back – move forth to minimum gap – move back to working gap (wedge procedure)

Slot die internal:
stop and redirect the flow by shutters and valves. Pump flow continues, die flow stops.

All 3 techniques (single or in combination) work quite well, if the viscosity is rather high and the required edge defintion is not more precise than around 1 mm. All techniques may be combined with a vacuum pump upstream to stabilize the meniscus and suck away residual liquid.

Structured coating – the switching slot die lip



Slot die with movable lips: coating mode

coating works as usual

L lip
V slot volume
B bendable lip
S bending slot

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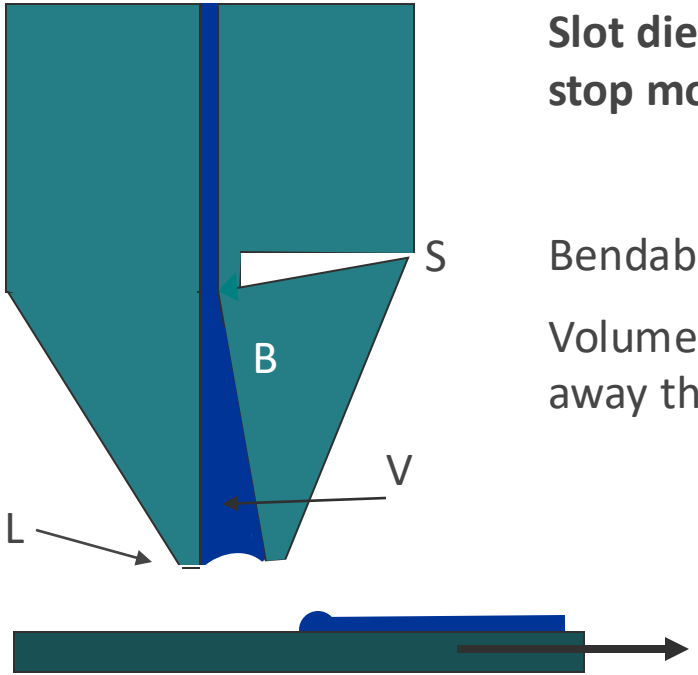
Structured coating – the switching slot die lip



Slot die with movable lips: stop mode

Bendable lip B flips open

Volume V increases and sucks away the meniscus

L lip
V slot volume
B bendable lip
S bending slot

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Technical implementation with bendable lips in action

5.

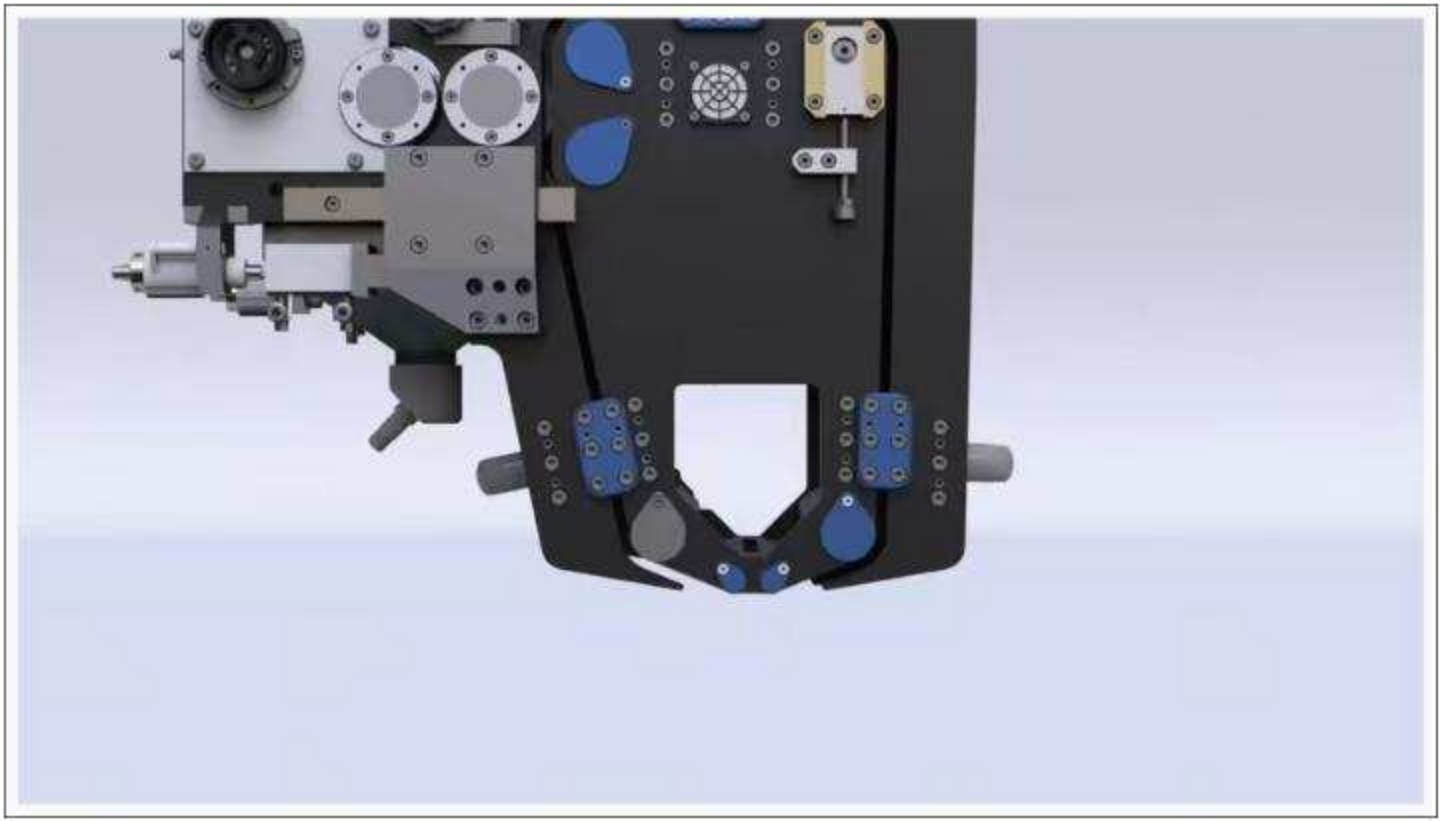
Digital application system

HELIO**SONIC**

PRINTING THE UNPRINTABLE

HELIOSONIC PRINTING TECHNOLOGY
CREATES NEW POTENTIAL
FOR INDUSTRIAL DIGITAL PRINTING
AND SIGNIFICANTLY IMPROVES
THE USE OF RESOURCES.

Technology
Droplet Generation



Technology
Inking & Printing

Value Proposition
Digitally deposited coatings

General
- Fully digital printing process without printing form
- Non-contact printing
- Multiple “wet-on-wet” printing
- Printing on sensitive substrates
- Tunable layer thickness 10-100µm
- Upper particle size limit ~ 100µm

Functional Inserts
- Sensors
  - Feature width 100µm+
  - Temperature
  - pH
  - Pressure and more
- Adhesives
- Sealants

Robustness
- Very robust and reliable process
  - No nozzle, slot or mesh clogging
  - Viscosity range of coatings/ inks from 10mPas to 1000mPas

Process Development Support
- Specific additives to make any ink HELIOSONIC compatible
- Broad know how based on optimized inks for complex designs
- Print parameter setting service

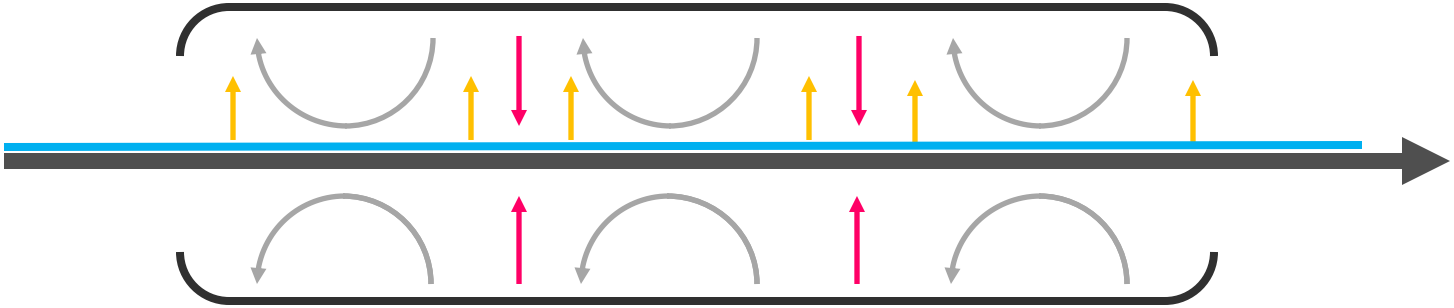
Precision
- Addressable 600dpi precision material deposition allows for:
  - Option for structured coatings with defined porosity/ channels
  - Sharp outlines
  - Non continuous coating (stop/ start) without reducing speed

Multi-material
- Combination of materials on dpi level; i.e.: -
  - Active/ inactive (inactive elements can be fillers or structural elements)
  - Conductive/ insulating

6.

Drying technologies

Introduction thermal drying – As general as possible(!?)



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

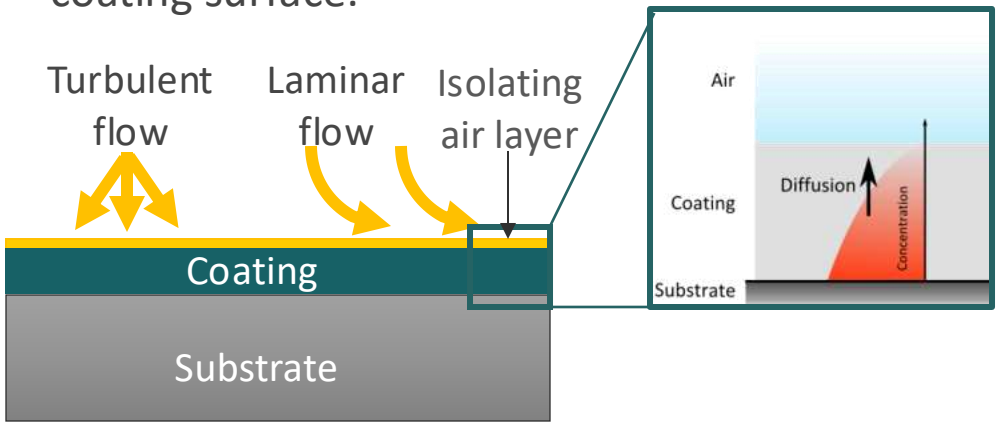
Substrate
Coating
Heat transfer
Evaporating solvent
Solvent vapor transfer

Mass Transfer

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.

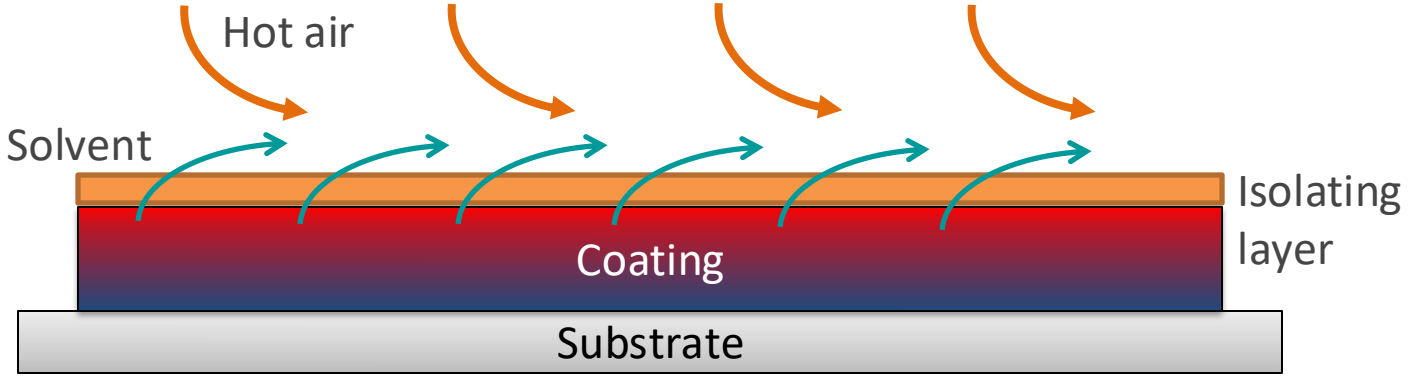


Usually there is a trade-off:

effective fast heat/mass transfer
or
gentle mild slow drying

Basics mass + heat transfer – Drying dynamics: Hot air drying

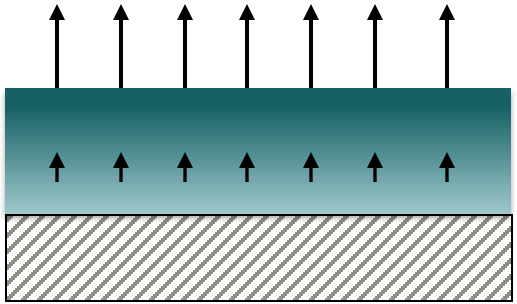
- ✓ Heating and vapor transport combined
- ✓ Bulk heating by thermal conductivity from surface
- ✓ Isolating layer to be overcome by air flow
- ✓ High air flow deteriorates surface
- ✓ Temperature easy to limit
- ✓ Slow



Basics mass + heat transfer

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.

Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

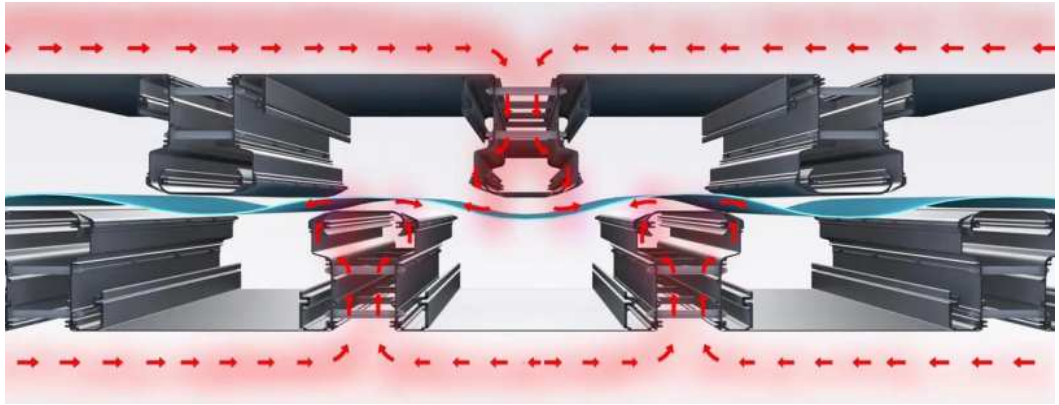
Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

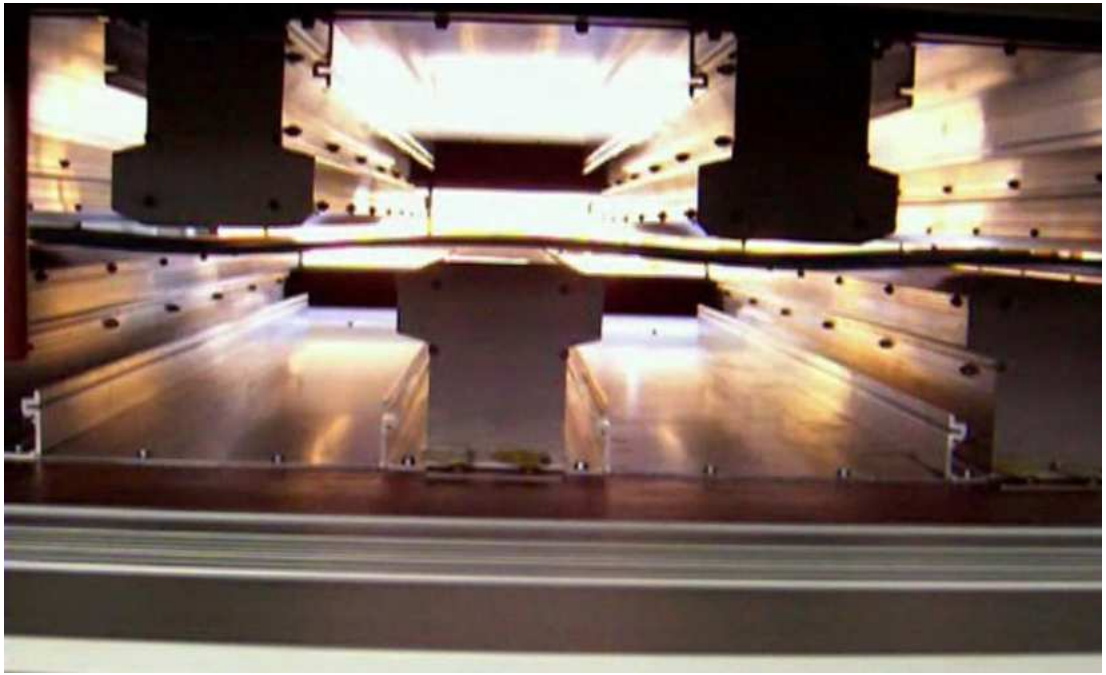
Coatema slot nozel and circulation dryer on small scale

Drytec Click&Coat™ dryer prinziple



Drying topics – drying technologies: HighDry HD500

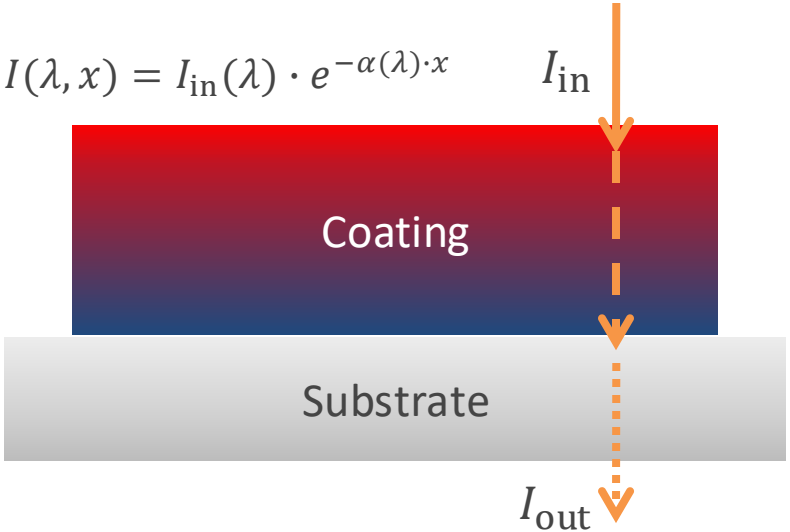
Web behaviour in a flowtation dryer



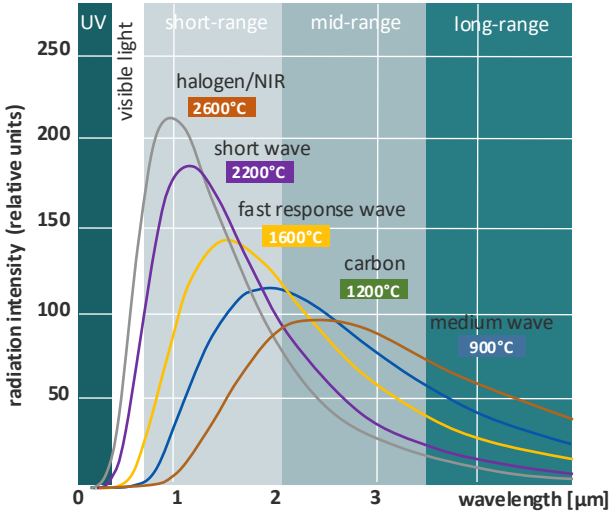
Press Button to show the video

Basics mass + heat transfer: (N)IR technology

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

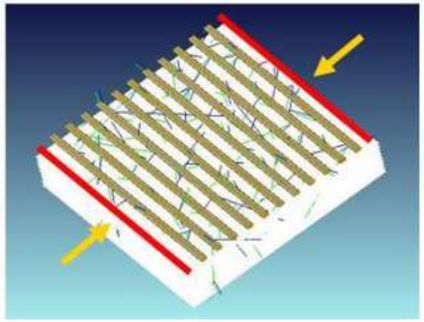


$I_{\text{in}}\ (\lambda)$	Intensity in
I_{out}	Intensity out
$\alpha(\lambda)$	Absorption coefficient
d	Layer thickness



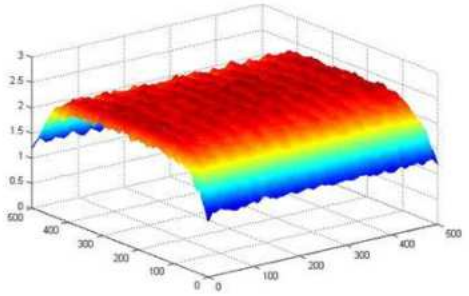
Relative intensity of radiators at different wavelengths

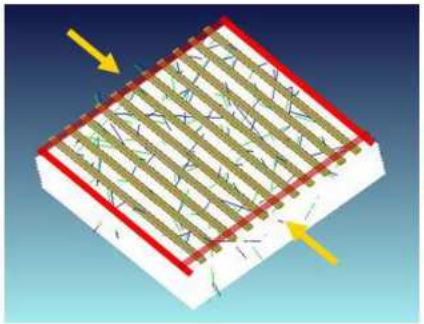
IR / NIR Drying – Infrared drying



Continuous process

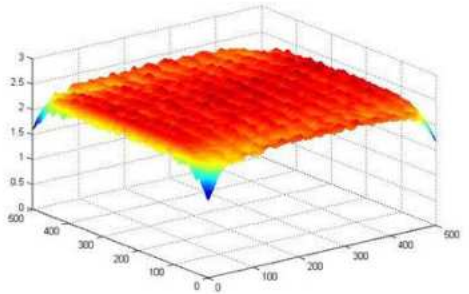
13 emitters, 2 types, 3 zones





Batch process

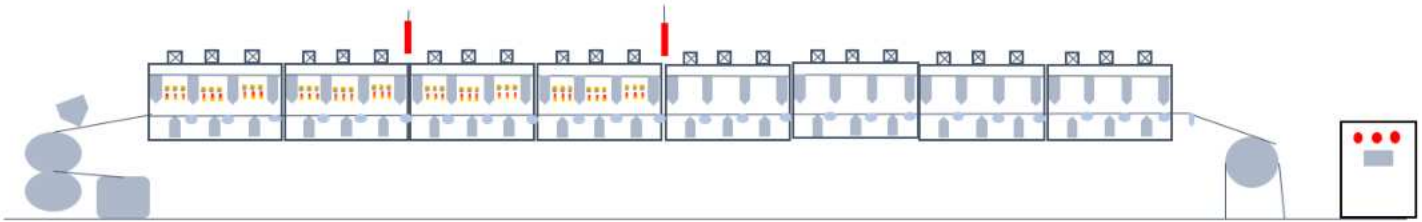
15 emitters, 3 types, 5 zones

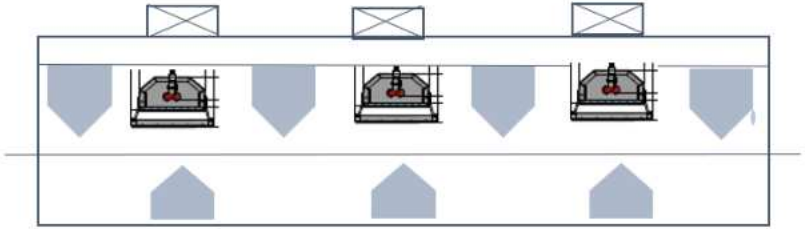


Soucre: Heraeus Noblelight

IR / NIR Drying – Infrared drying

Layout





Hotair oven: 50m (10 zone)

IR at first 25m (5 zone) for boost

Heating distance : 100mm

Qty of IR : 60 *3.1Kw = 186Kw

Soucre: Heraeus Noblelight

7.

Simulation

Slot die chamber – Simulation parameters

- ✓ Example for anode coating
- ✓ Copper substrate
- ✓ Pseudo-Carreau Fluid match power law (µinf=1mPas time-constant =1 sec)
- ✓ Typical Coatema Slot die
- ✓ Process parameters for 90m/min 400µm coating in 300 mm width

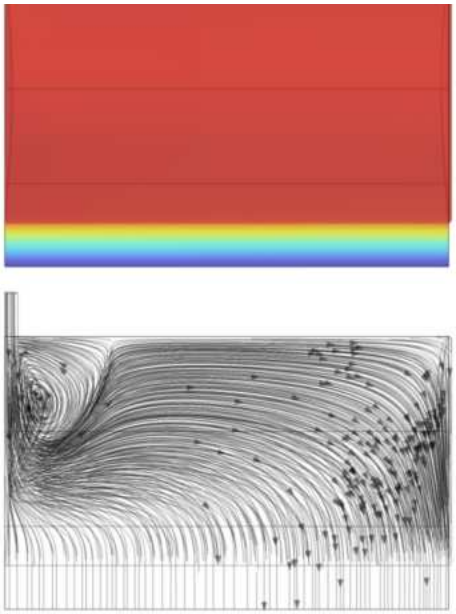
Name	Expression	Value	Description
W	0.8[mm]	8E-4 m	Slot gap
Hc	5[mm]	0.005 m	Inlet height
W_dd	1[mm]	0.001 m	Die width downstream
W_ud	1[mm]	0.001 m	Die width upstream
alpha_u	35[deg]	0.61087 rad	Upstream die angle
alpha_d	35[deg]	0.61087 rad	Downstream die angle
L_u	4.5[mm]	0.0045 m	Upstream length
L_d	10[mm]	0.01 m	Downstream length
H	0.7[mm]	7E-4 m	Coating gap
U_wall	90[m/min]	1.5 m/s	Coating velocity
m_power...	24.08	24.08	Estimated parameter m
gammadot	0.01	0.01	Shear rate optimization p...
n_powerL...	0.49	0.49	Estimated parameter n
Hcoat	0.4[mm]	4E-4 m	Coating Thickness
phi_die	25.9[deg]	0.45204 rad	Contact Angle Fluid-die
phi_sub	24[deg]	0.41888 rad	Contact Angle Fluid-Sub...
gamma_fl...	51.32[mN/m]	0.05132 N/m	Surface Tension Fluid

3D Homogeneity – Slot die chamber – Simulation of anode coating

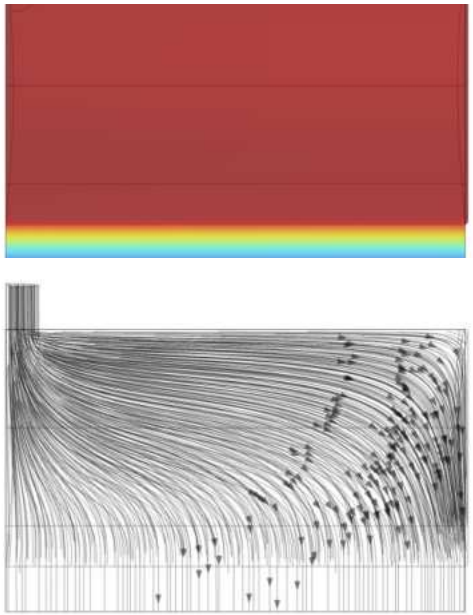
- ✓ Example for anode electrode coating
- ✓ Fluid data taken from real world (shear-thinning power law fluid)
- ✓ Process parameters for 90m/min 400µm coating and 300 mm width
- ✓ No „fancy" slot-die „just" Coatema standard

3D Homogeneity – Slot die chamber – Streamlines and pressure distribution

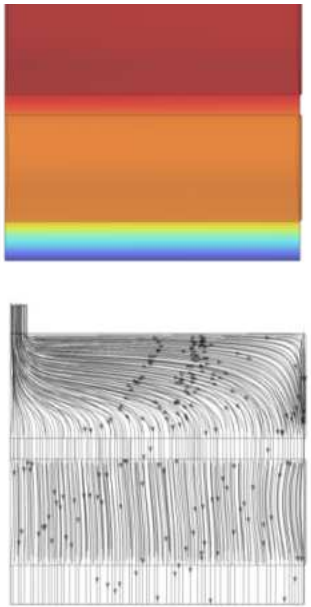
Single Chamber with too small inlet (4 mm)



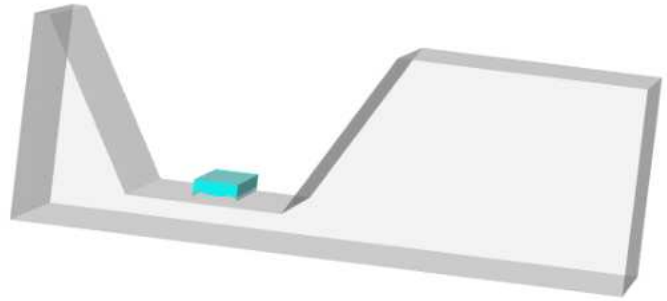
Single Chamber with correct chamber layout (10 mm inlet)

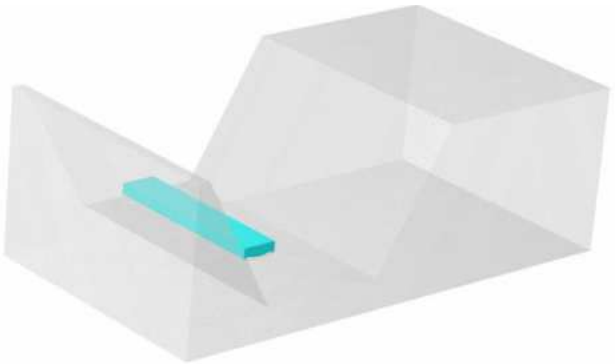


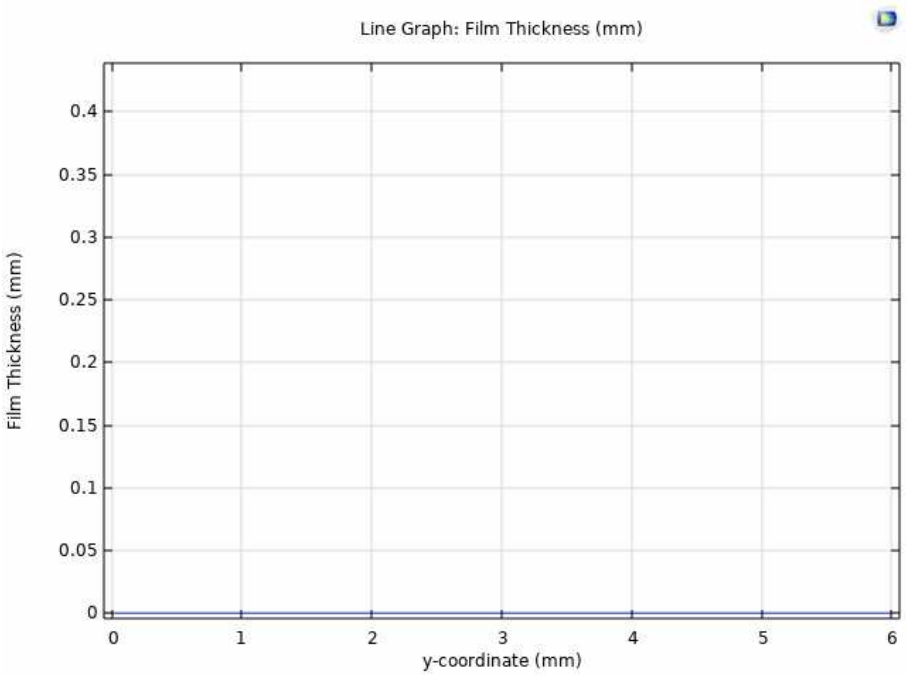
Dual chamber slot die (8 mm inlet same dead volume)



3D Homogeneity – Slot die chamber – Meniscus makes or breaks Homogeneity







8.

Summary

Outlook

- ✓ Latest 2030 – 2050 the whole automotive car fleet has to be zero emission
- ✓ Impact markets will be automotive, light / heavy trucks, trains and decentralized power supply
- ✓ New green deal of the European Comission
- ✓ Markets will be PEMFC / HTPEMFC / SOFC / AFC / PEM Electrolyzer
- ✓ Coatema has over 22 years experience in the market of fuel cell equipment
- ✓ Electrolyzer to produce green hydrogen out of renewables will be the boom market in the next years to come and Coatema wants to be a part of it

Do not hesitate to contact us!

Anything missing?

Let us know and we will make it happen!

Our R&D centre is worldwide the most versatile centre for coating, printing and laminating.

Sales department:
sales@coatema.de

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