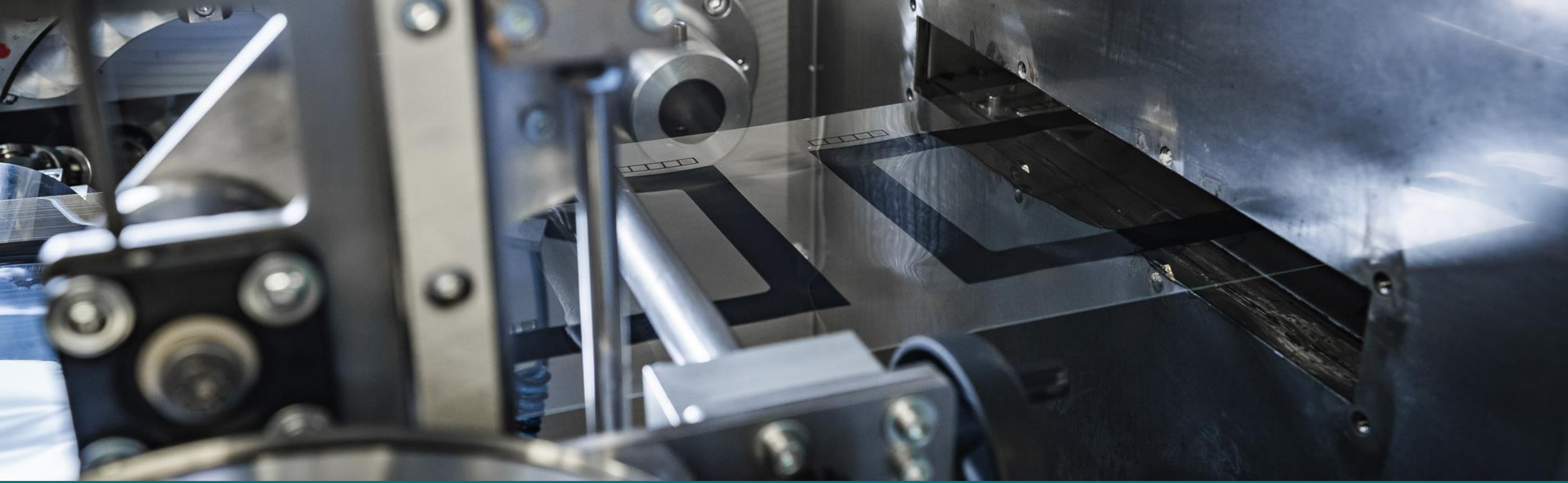


Technology development and manufacturing for fuel cells and electrolyzers

Coatema

02/06/25

MEMBER OF ATH

Agenda

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

1.

Introduction Coatema

Coatema® Coating Machinery GmbH

Overview

Quality
made in Germany

Part of the ATH Holding

S2S equipment

R2R equipment

Innovations

Coating

Printing

Laminating

Bespoke
equipment

Founded
1974

Printed electronics
Fuel cells
Membranes
Pharmaceutics
Solar
Batteries
Prepregs
Green Hydrogen

From lab 2 fab

R&D
projects & network

Worldwide
service

Coatema® Coating Machinery GmbH

Group of companies

ATH 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

Coatema® Coating Machinery GmbH

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

Coatema services as an overview

The Coatema R&D centre

Accelerate your innovation in our dedicated pilot facility with advanced lab & pilot lines and expert guidance – bridging the gap from #lab2fab.

The Coatema Coating Symposium

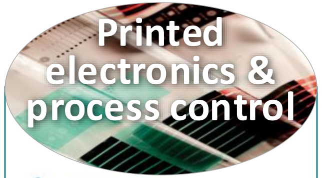
Join the global network of coating experts at our annual event, where cutting-edge developments meet industry collaboration for next-level innovation.

The Coatema Slot Die Masterclass

Master precision coating in our hands-on training program, led by industry specialists to optimize slot-die performance and product excellence.

Coatema® Coating Machinery GmbH

R&D projects overview 2022 – 2025

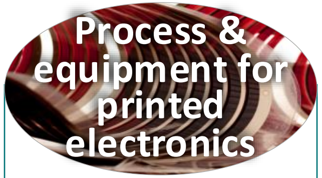


REAL NANO

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

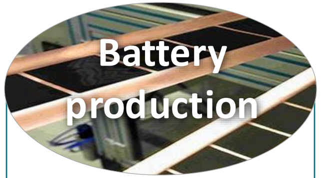


FLEX2ENERGY – AUTOMATED MANUFACTURING PRODUCTION LINE FOR IPVS

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

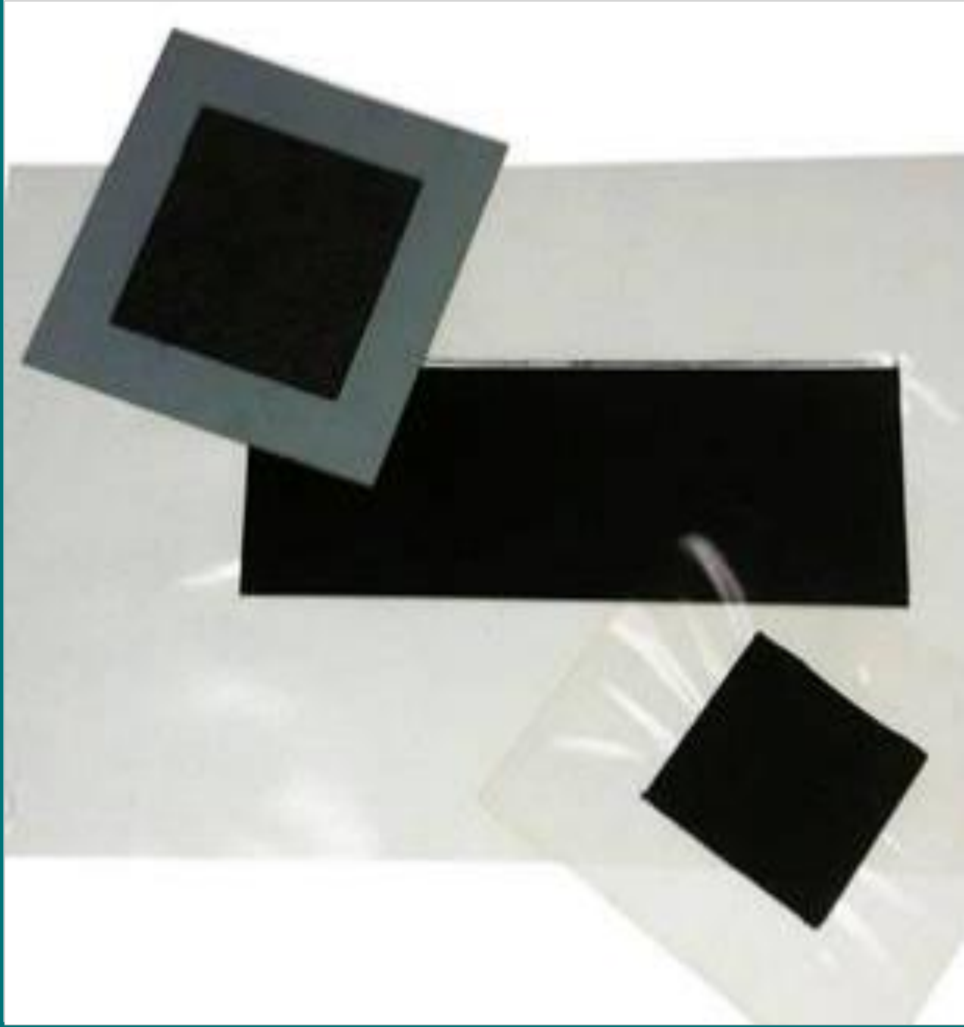
Creating an open-innovation testbed for sustainable packaging

R&D network

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
Fraunhofer ISC
Fraunhofer FEP
Fraunhofer IVV
Fraunhofer ISE
Fraunhofer ICT
Fraunhofer PYCO
Fraunhofer IPT
Fraunhofer IWM

2.

Today‘s equipment for todays fuel cells/electrolyzers



Coatema® Coating Machinery GmbH

Our equipment solutions for electrolyzer / fuel cell

Coatema

CCM Manufacturing

GDL / GDE

- GDL → Micro porous layer → Drying → Catalyst → Drying → GDE

CCM

- A → Membrane → Catalyst → Drying → CCM
- B → Membrane → Catalyst → Drying / Membrane → Catalyst → Drying → CCM
- C → Membrane → Top catalyst / Bottom catalyst → Drying → CCM

CCM / Decal

- A → Carrierfilm 1 → Catalyst → Drying / Carrierfilm 2 → Catalyst → Drying → CCM
- B → Membrane → Carrierfilm 1 / Carrierfilm 2 → Hot pressing → Delamination → CCM

Membrane

- A → Casting → Wet lamination → Drying → Membrane

Legend:

- Input
- Process
- Output

CCM = Catalyst Coated Membrane

GDL = Gas Diffusion Layer

GDE = Gas Diffusion Electrode

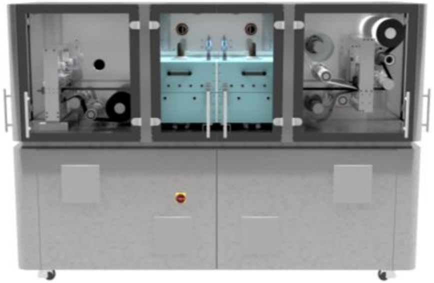
MEA = Membrane Electrode Assembly

S2S

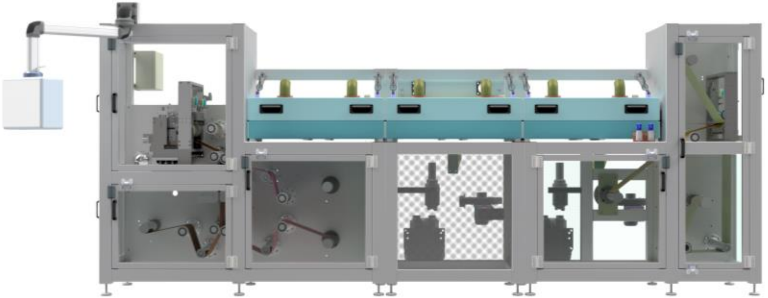
Coatema*2go*	Easycoater	Easycoater Evolution
Ink testing	First sample product	First pilot as S2S

Coatema®
Coating Machinery GmbH

Roll-to-Roll (R2R) lab systems

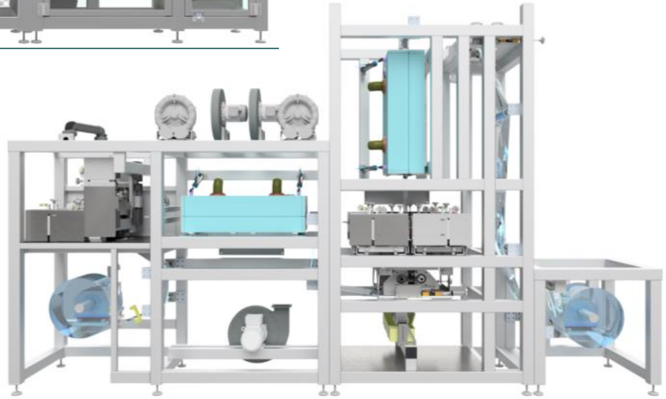


Test Solution R2R



Basecoater R2R

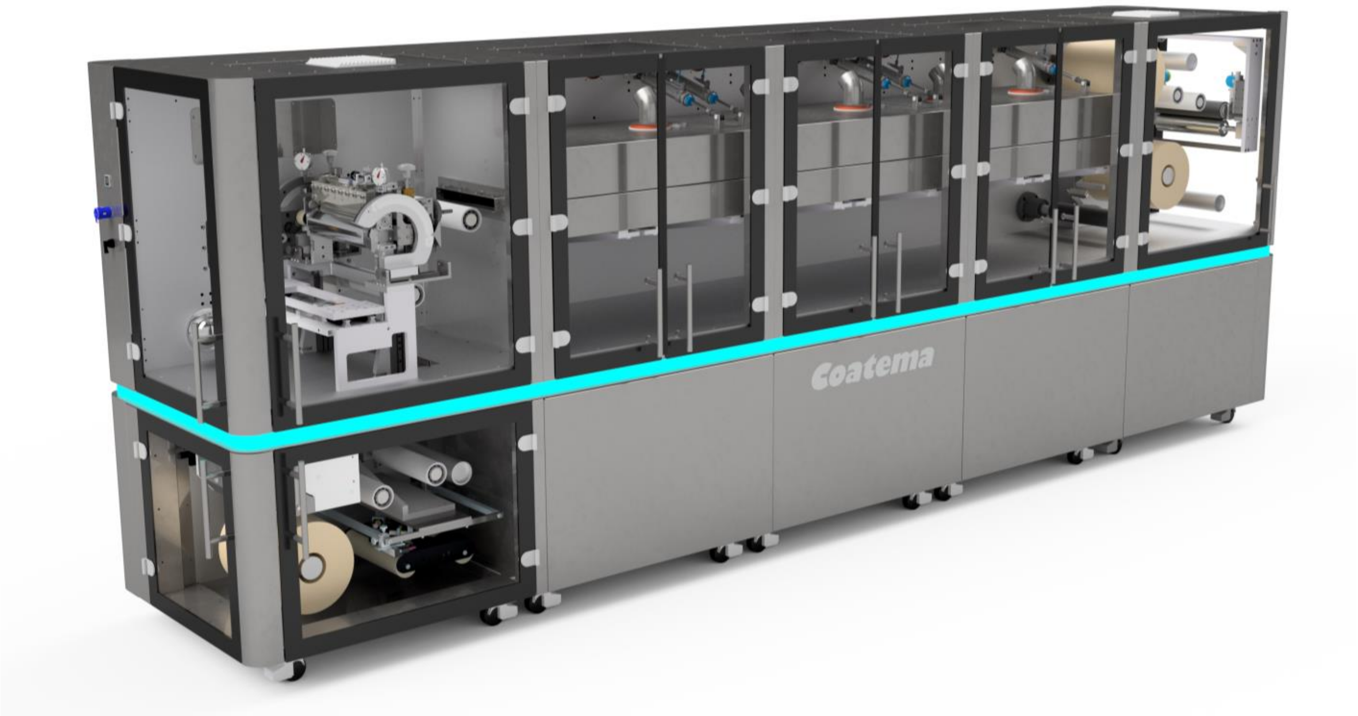
Smartcoater R2R



Verticoater R2R

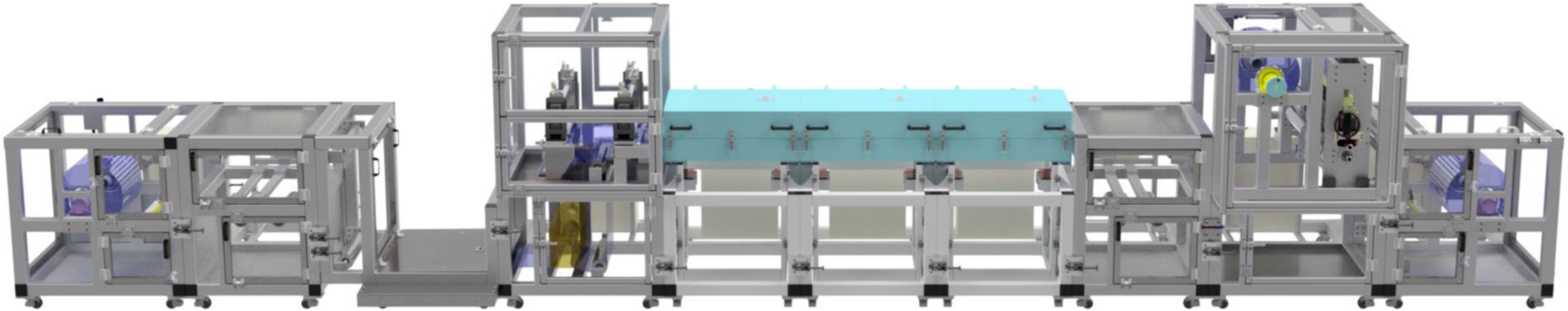
The Smartcoater

The Smartcoater



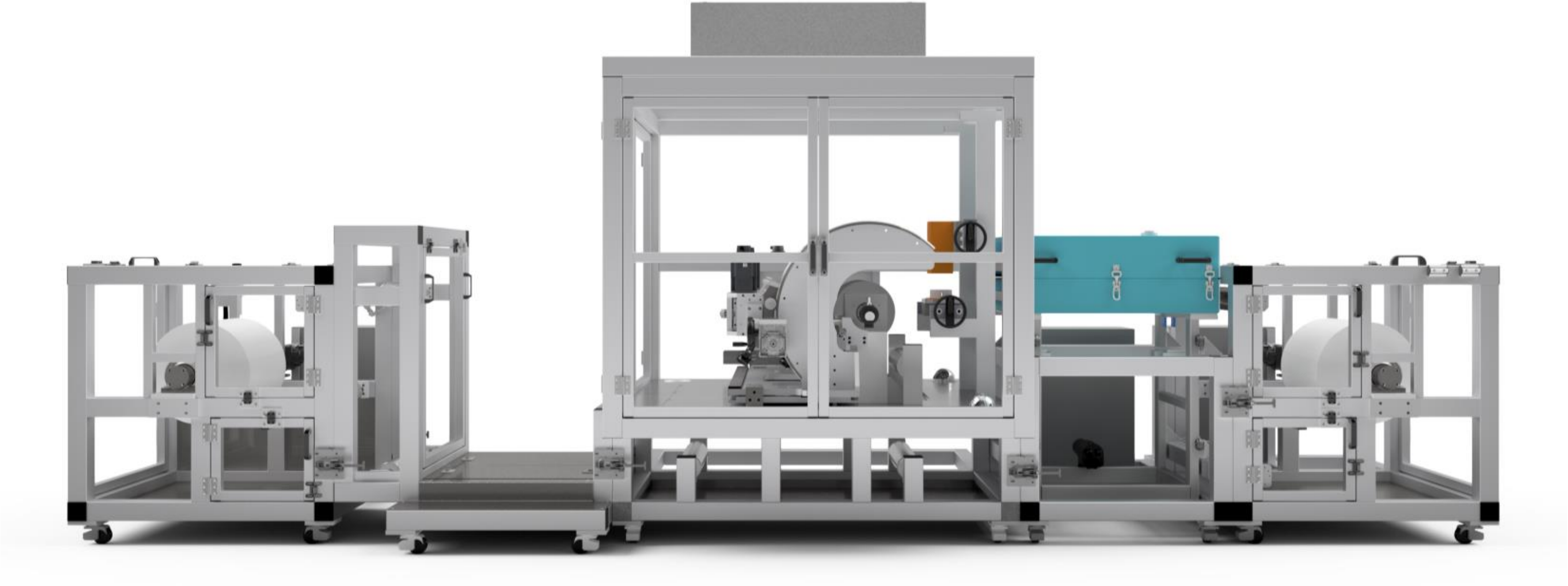
Roll-to-Roll (R2R) pilot

Basecoater Pilot R2R

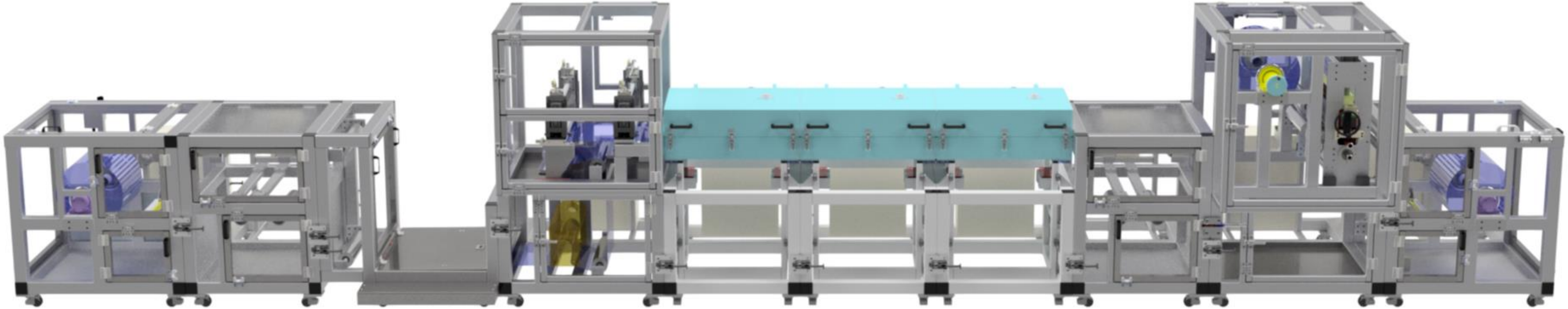


Click&Coat^{TM} R2R

The Click&Coat™

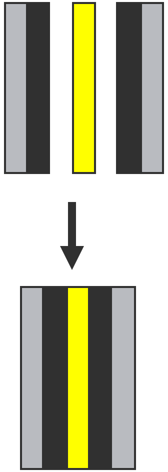


The Click&Coat^{TM}

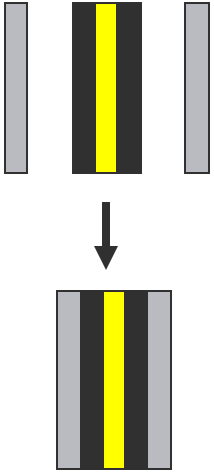


GDE and CCM coating lines

GDE method



CCM direct

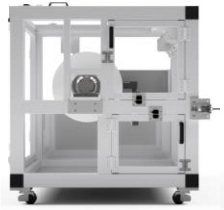


The Click&Coat™

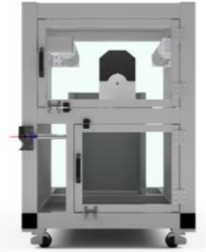
The Click&Coat^{TM}

Specific equipment in Click&Coat^{TM} layout

Click&Coat™ your own ideas



Winder



Corona

Podestral

Coating

Printing

Dryer

Laminator

Rewinder

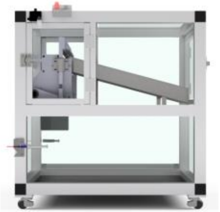
Chemical treatment bath

Inert Coating and laminating

Registration control

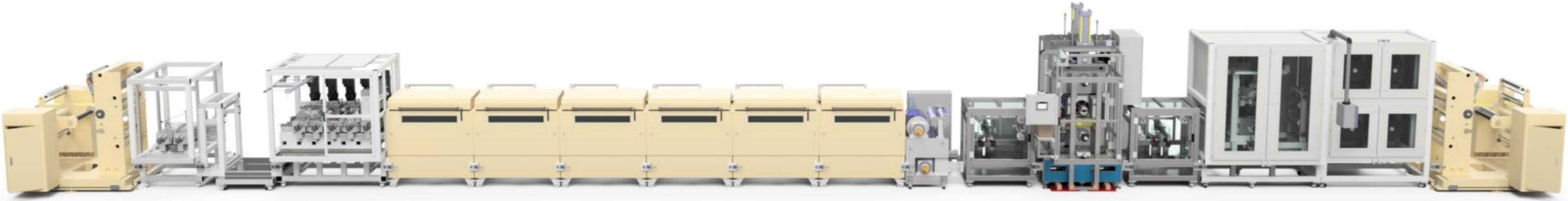
Turning device

Lamination



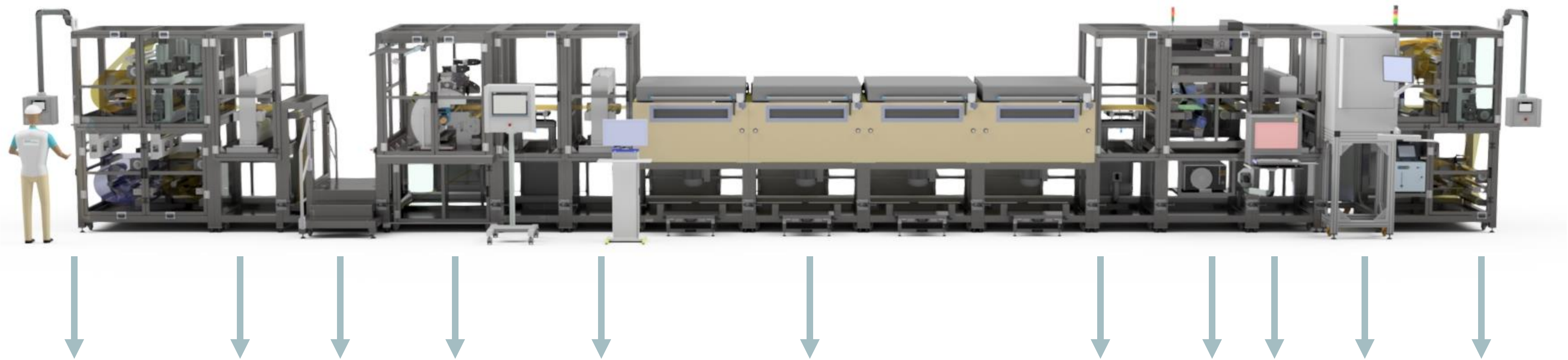
Cutting

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

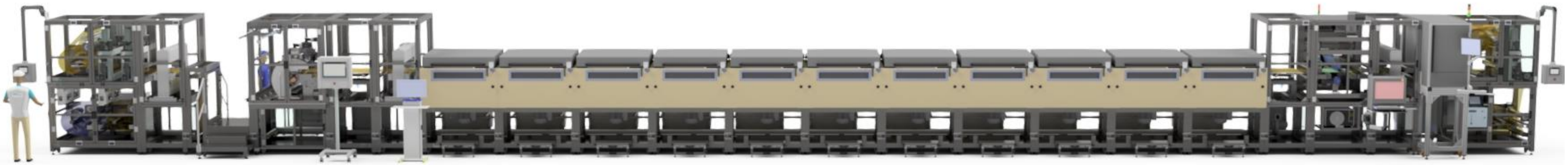
- ✓ Lamination
- ✓ Thickness measurment
- ✓ Dry coating

- ✓ XRF - measurment
- ✓ Platinium loading

- ✓ Thickness measurment
- ✓ Substrate

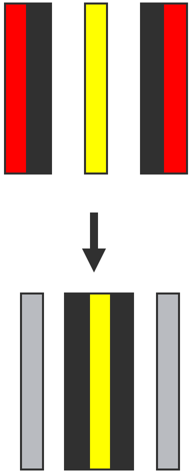
The Click&Coat^{TM} in production scale

The Click&Coat^{TM} in production scale

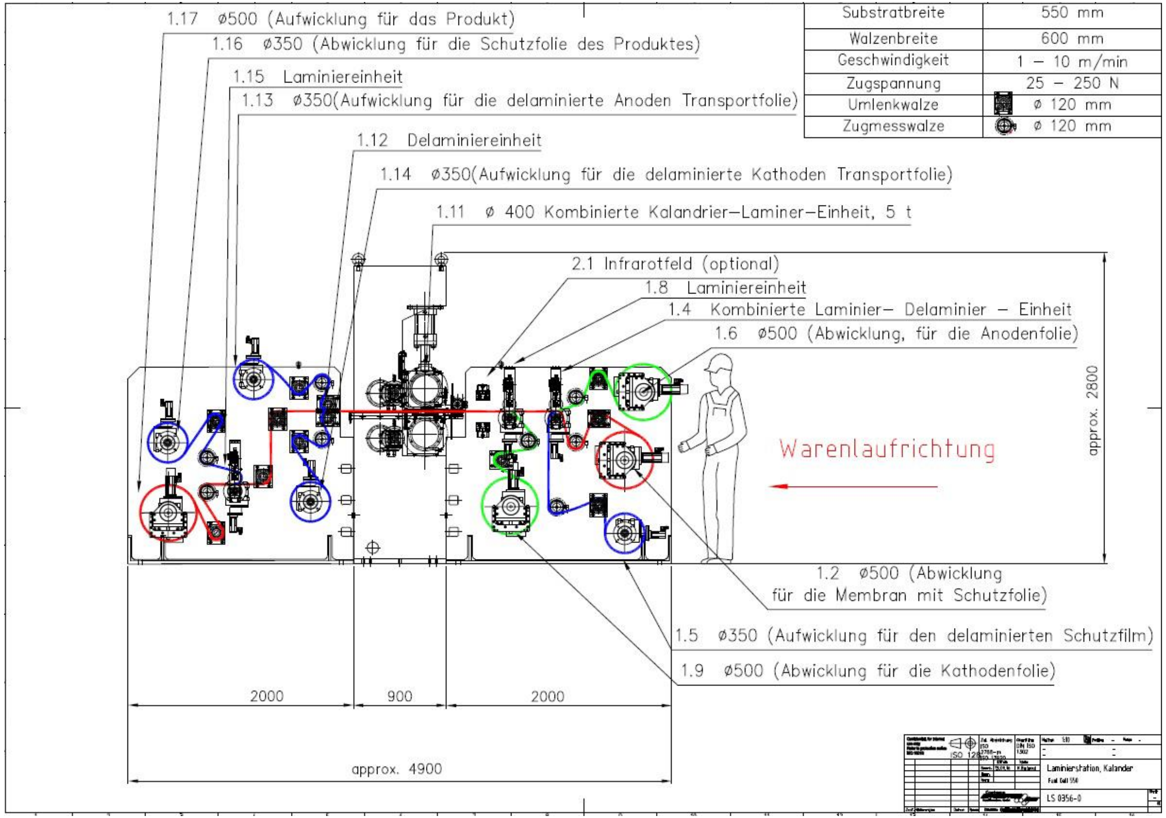


Indirect CCM (Decal) Method

CCM indirect

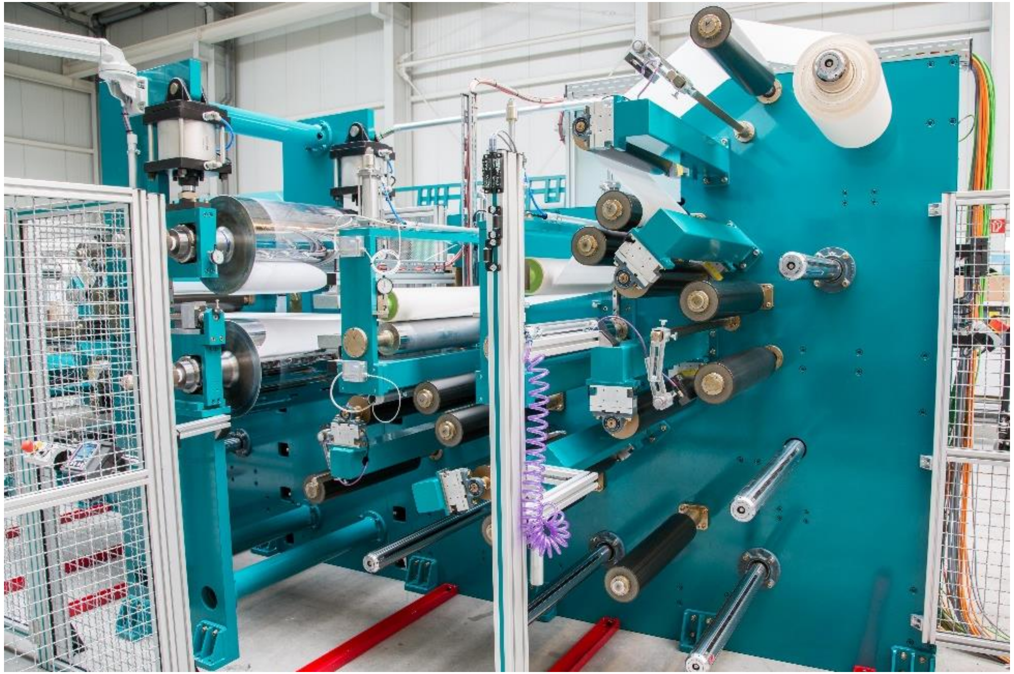


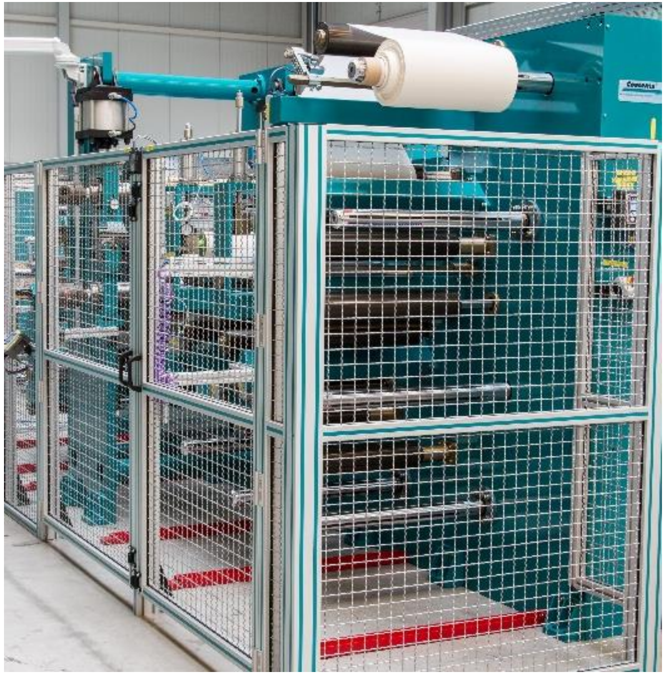
Decal 3rd Generation



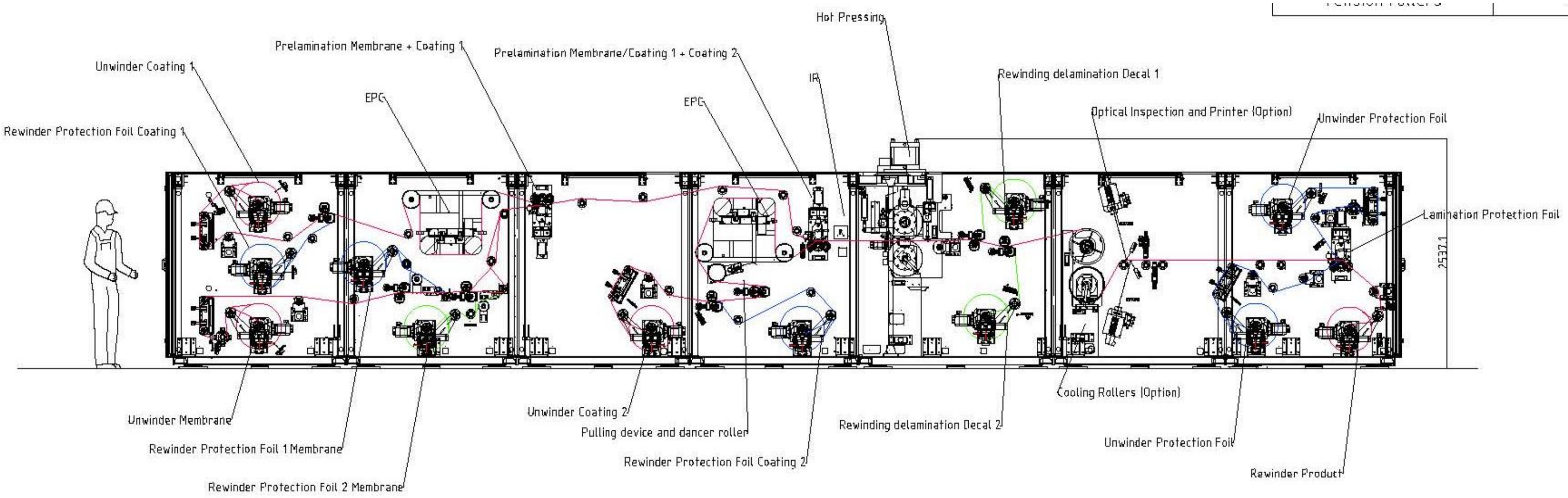
Substratbreite	550 mm
Walzenbreite	600 mm
Geschwindigkeit	1 – 10 m/min
Zugspannung	25 – 250 N
Umlenkwalze	ø 120 mm
Zugmesswalze	ø 120 mm

Hot pressing



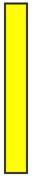


Decal 3rd Generation



Membrane casting and reinforced membrane (wet lamination)

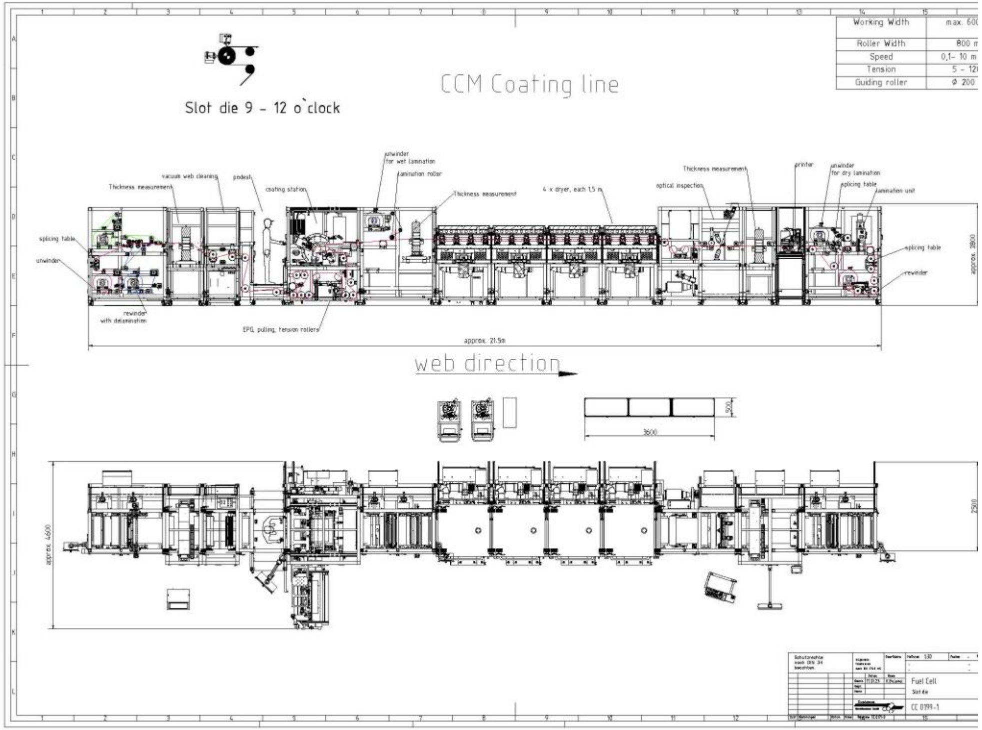
Membrane (Casting)



Reinforced Membrane (wet lamination)

Membrane casting

Membrane casting



Production line for fuel cells – 1000 mm working width

3.

Coating systems

Coating parameters

Coating chemistry

- ✓ Rheology
- ✓ Viscosity
- ✓ Viscoelasticity
- ✓ Type of solvents
- ✓ Solid content
- ✓ Van der Waals force
- ✓ Sheer ratio
- ✓ Adhesion/Cohesion

Coating processes

- ✓ Coating systems
- ✓ Single or multilayer coatings
- ✓ Direct coatings
- ✓ Transfer (indirect) coatings
- ✓ Substrate speed
- ✓ Layer thickness
- ✓ Coating accuracy

Process control

- ✓ Process layout
- ✓ Tension control system
- ✓ Material guiding system
- ✓ Inline parameter control
- ✓ Quality control

Drying

- ✓ Convection drying
- ✓ Contact drying
- ✓ Infrared drying
- ✓ Sintering
- ✓ NIR
- ✓ High frequency
- ✓ UV crosslinking systems

Substrate

- ✓ Surface tension
- ✓ Dimension stability
- ✓ Surface structure
- ✓ Contact angle

Pretreatment

- ✓ Corona
- ✓ Plasma
- ✓ Cleaning

Environment

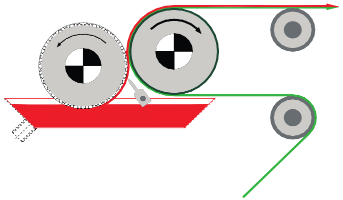
- ✓ Humidity
- ✓ Temperature
- ✓ Inert conditions

Finishing

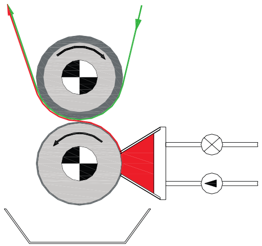
- ✓ Calendaring
- ✓ Embossing
- ✓ Slitting

Coatema® Coating Machinery GmbH

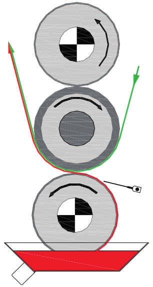
Printing systems



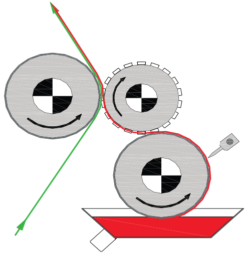
Engraved roller system



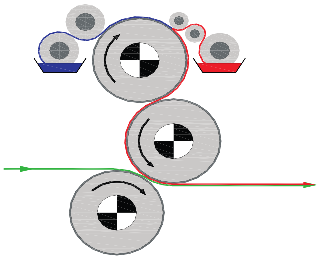
Gravure roller system



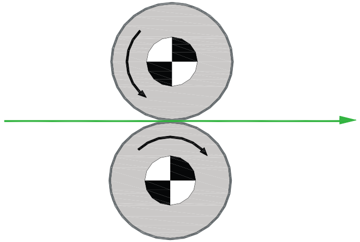
Gravure indirect system



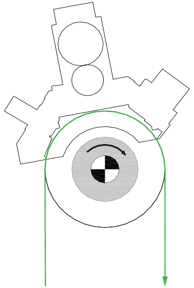
Flexography system



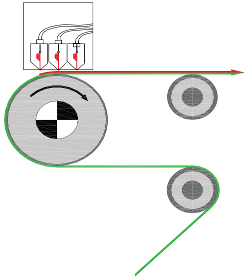
Offset lithography system



Hot embossing system

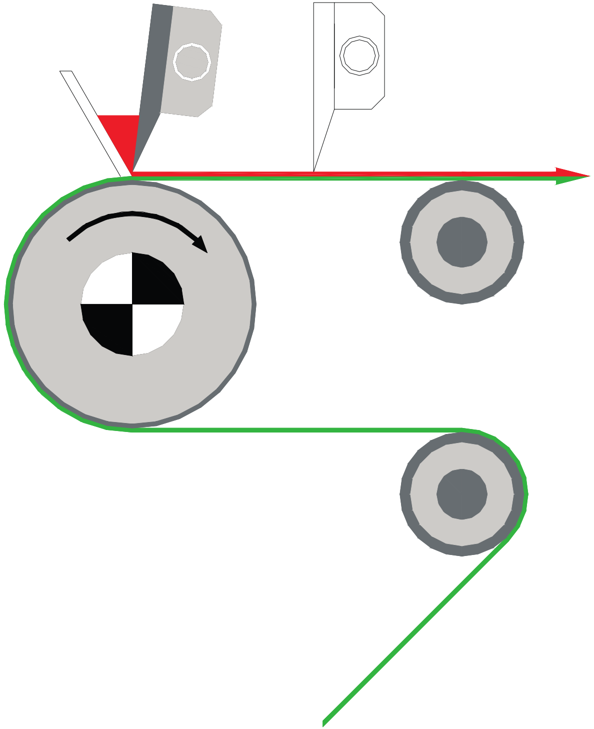


Nanoimprint system



Inkjet system

Knife coating



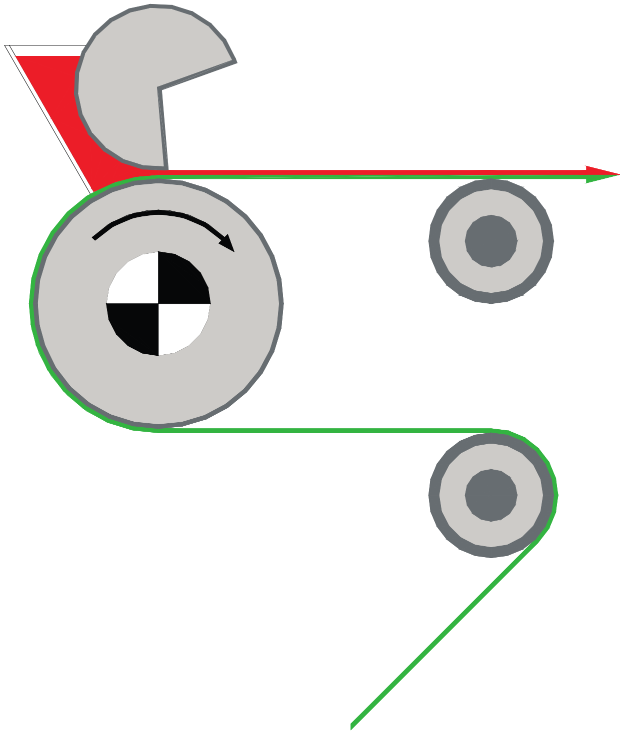
Variation of the coating weight

- ✓ 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/m^2

Range of viscosity

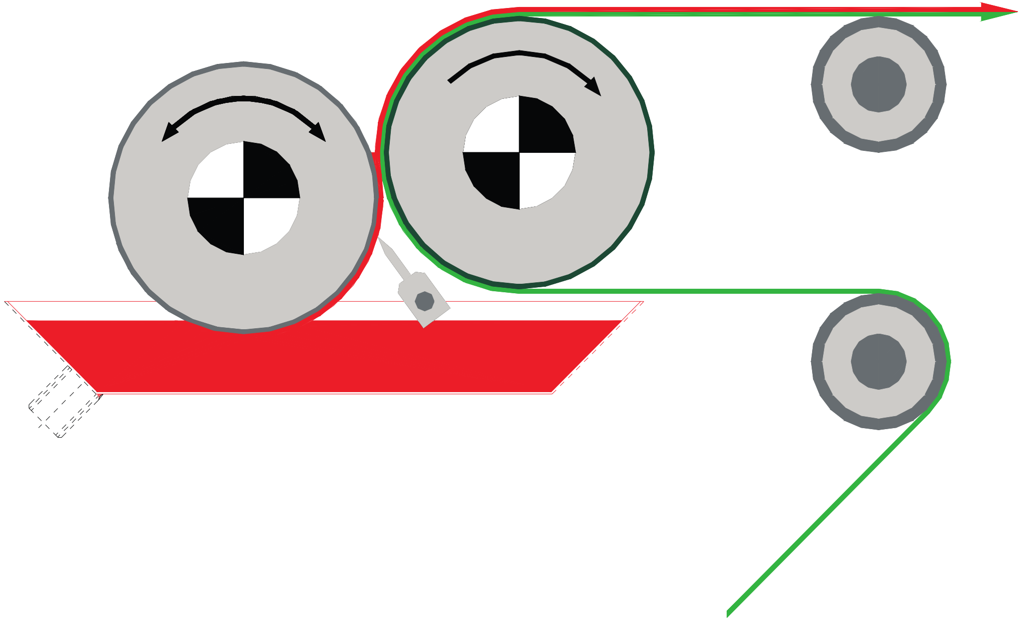
✓ Paste

5 – 6 to 60 g/m^2

✓ Foam

10 000 – 25 000 mPas

Gravur coating



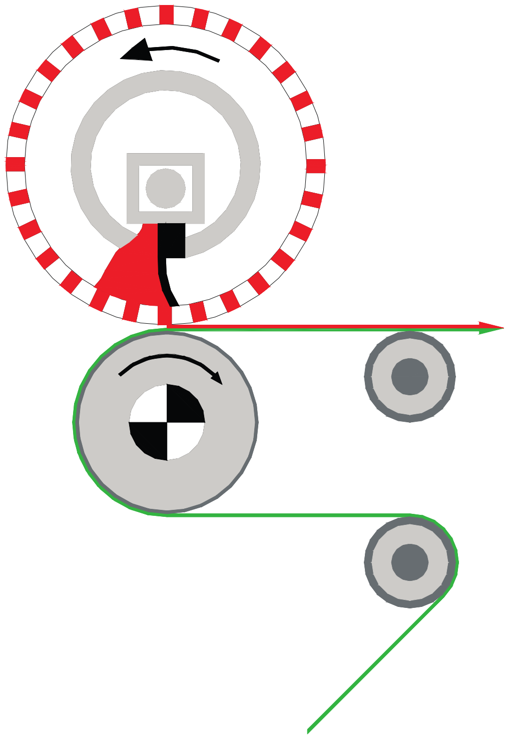
Variation of the coating weight

✓ 2 – 200 g/m²

Range of viscosity

✓ 1 – 15 000 mPas

Rotary screen coating



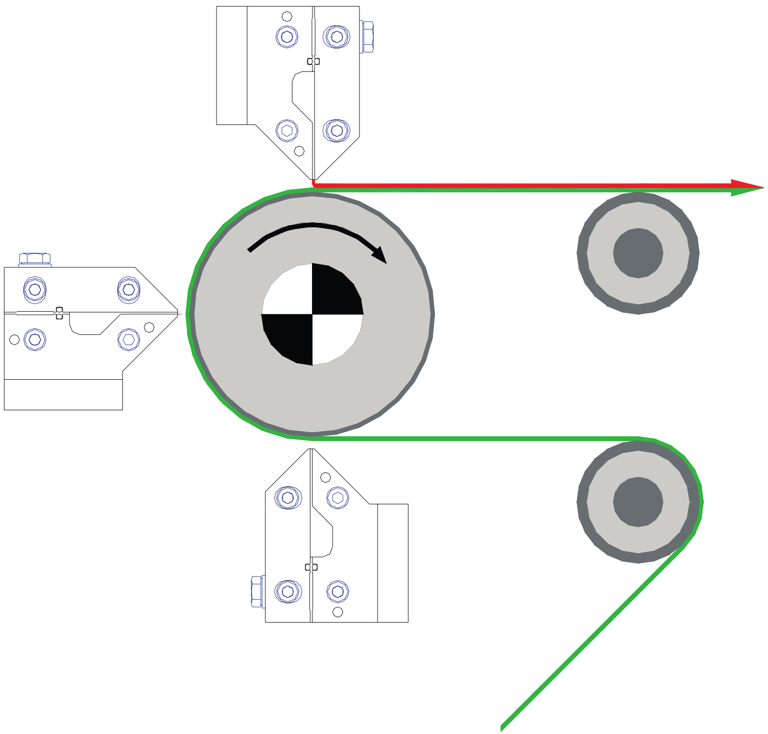
Variation of the coating weight

- ✓ 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

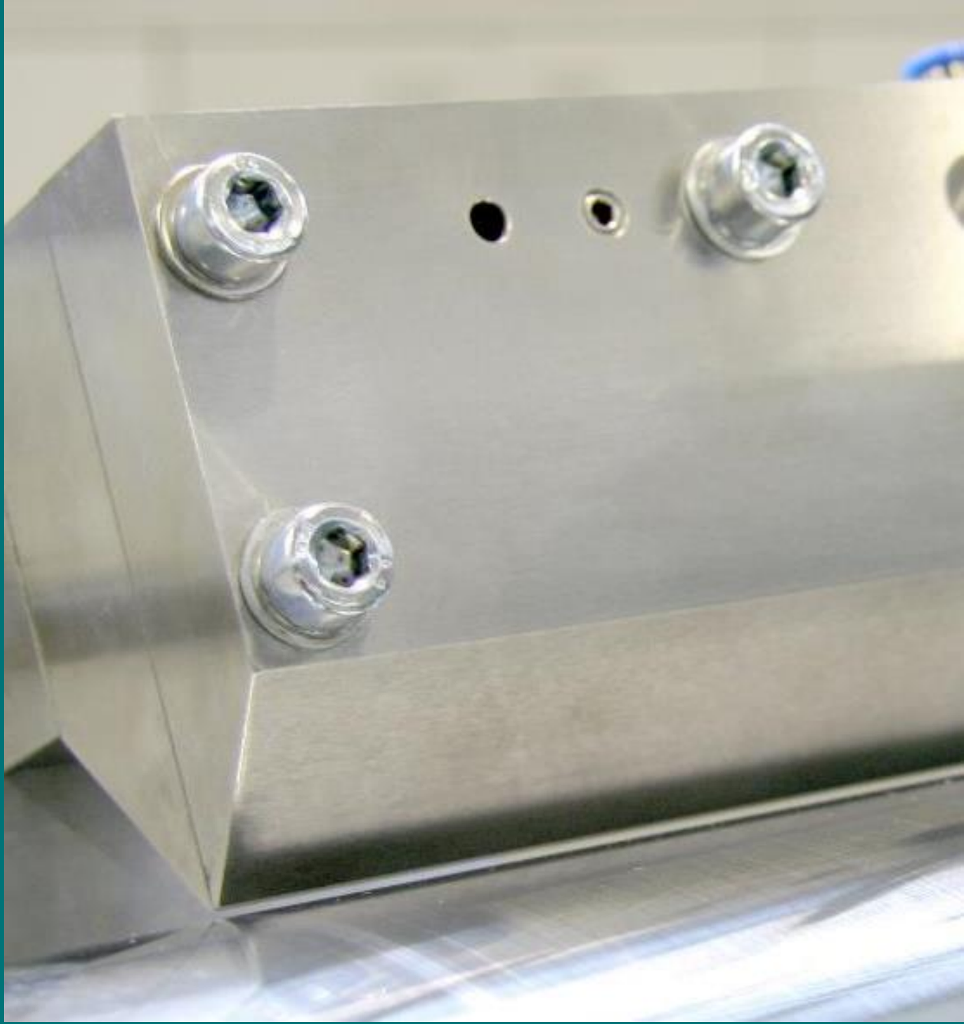
✓ 1 – 200 g/m²

Range of viscosity

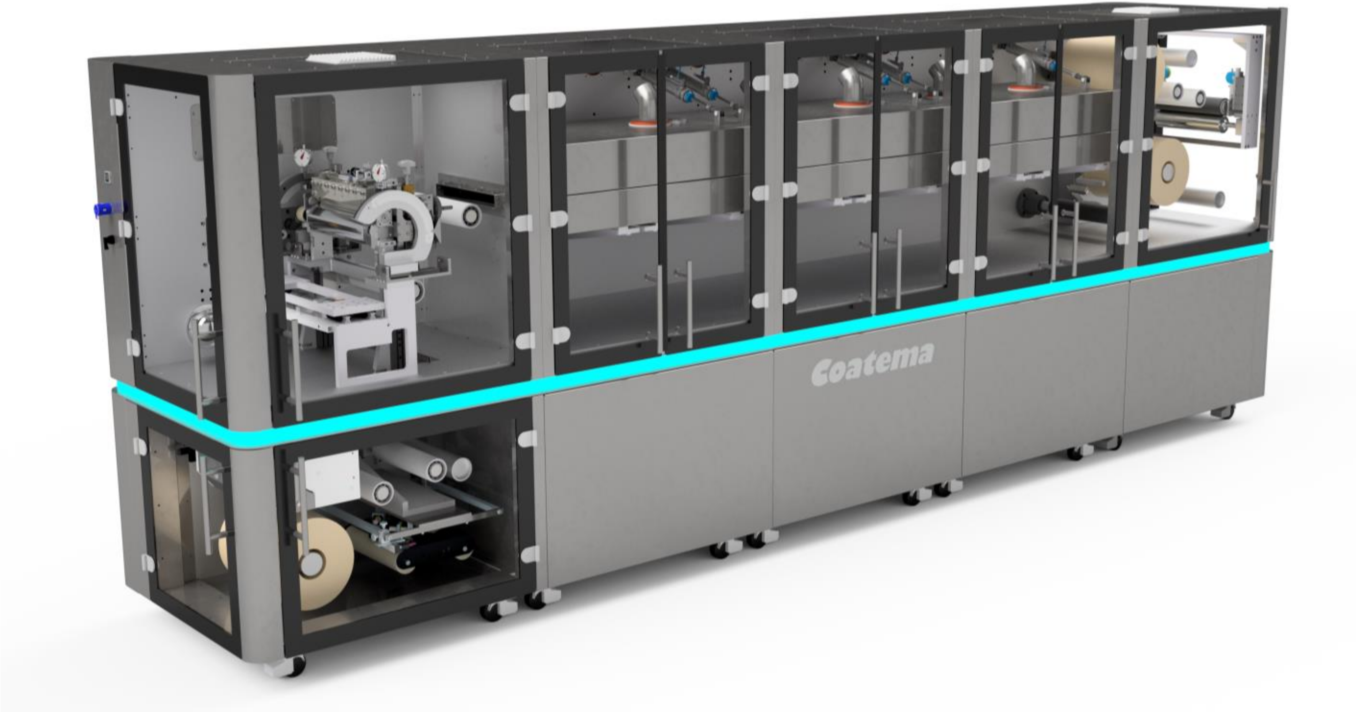
✓ 1 – 30 000 mPas

4.

Slot die coating for fuel cells



Basic principle



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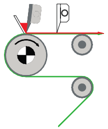
Coating parameters

Ink properties	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

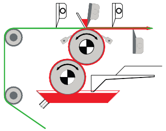
Substrate	Pretreatment	Environment	Finishing
✓ Surface tension ✓ Dimension stability ✓ Surface structure ✓ Contact angle	✓ Corona ✓ Plasma ✓ Cleaning	✓ Humidity ✓ Temperature ✓ Inert conditions	✓ Calendaring ✓ Embossing ✓ Slitting

Slot die coating for fuel cells

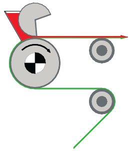
Coating systems



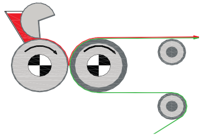
Knife system



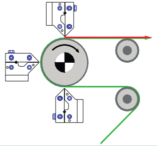
Double side coating system



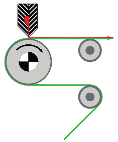
Commabar system



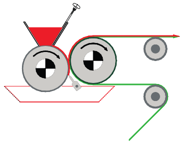
Reverse commabar system



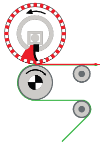
Slot die system



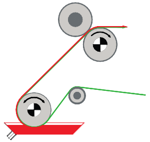
Curtain coating system



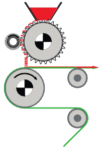
Case knife system



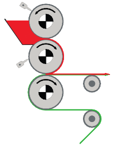
Rotary screen system



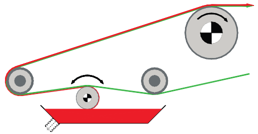
Dipping system (Foulard)



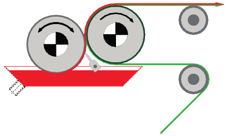
Powder scattering system



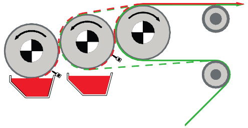
Reverse roll coating system



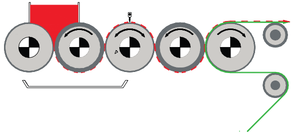
Micro roller coating system



2-roller coating system

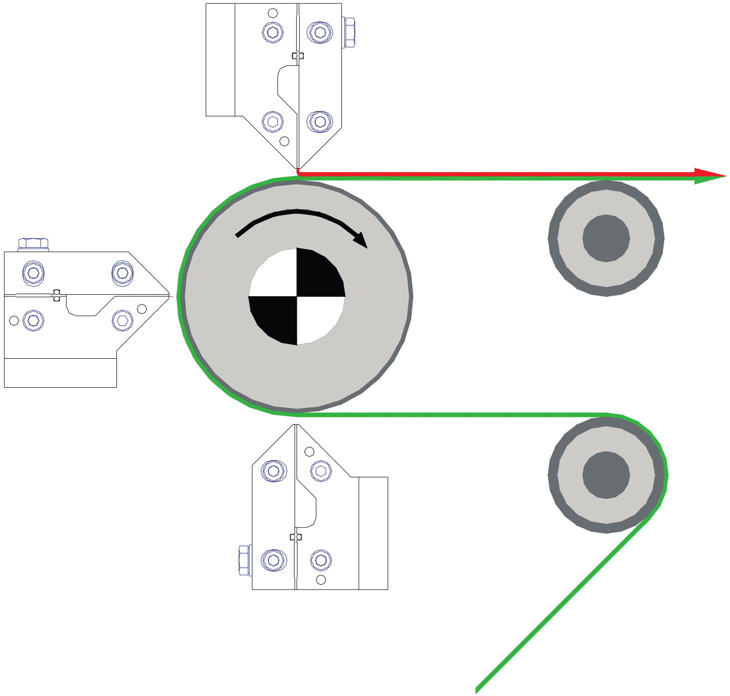


3-roller combi coating system



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

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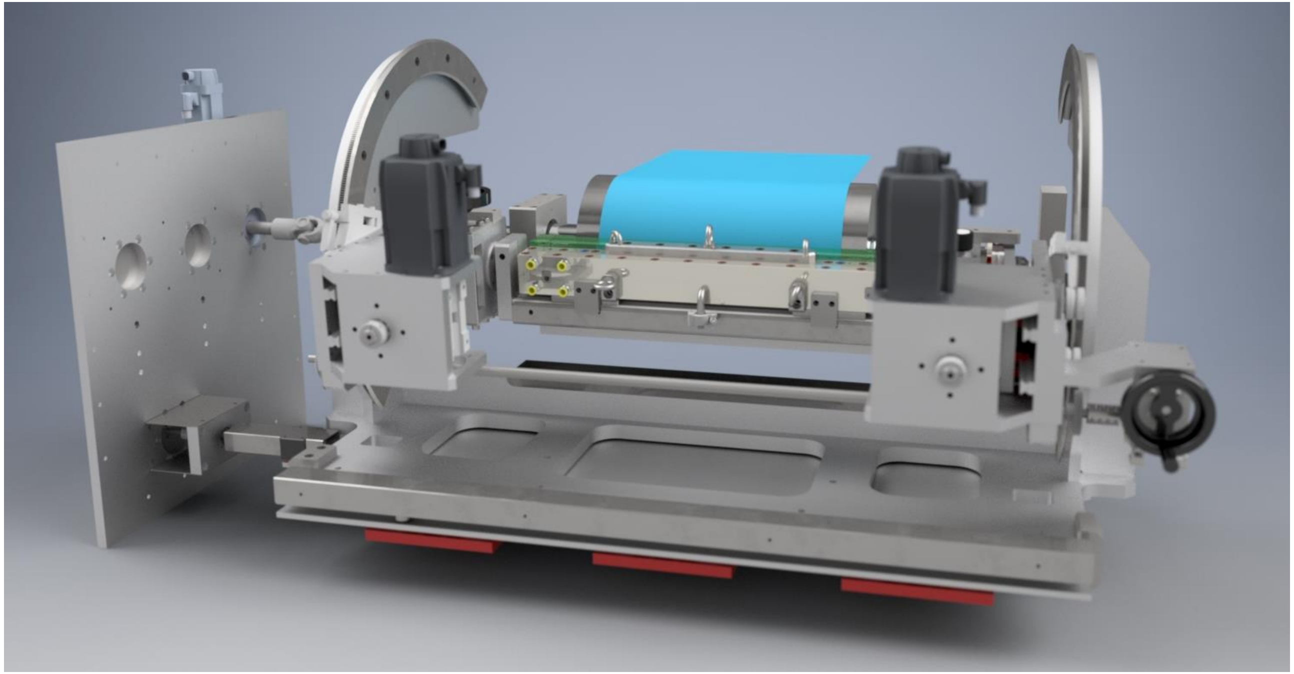
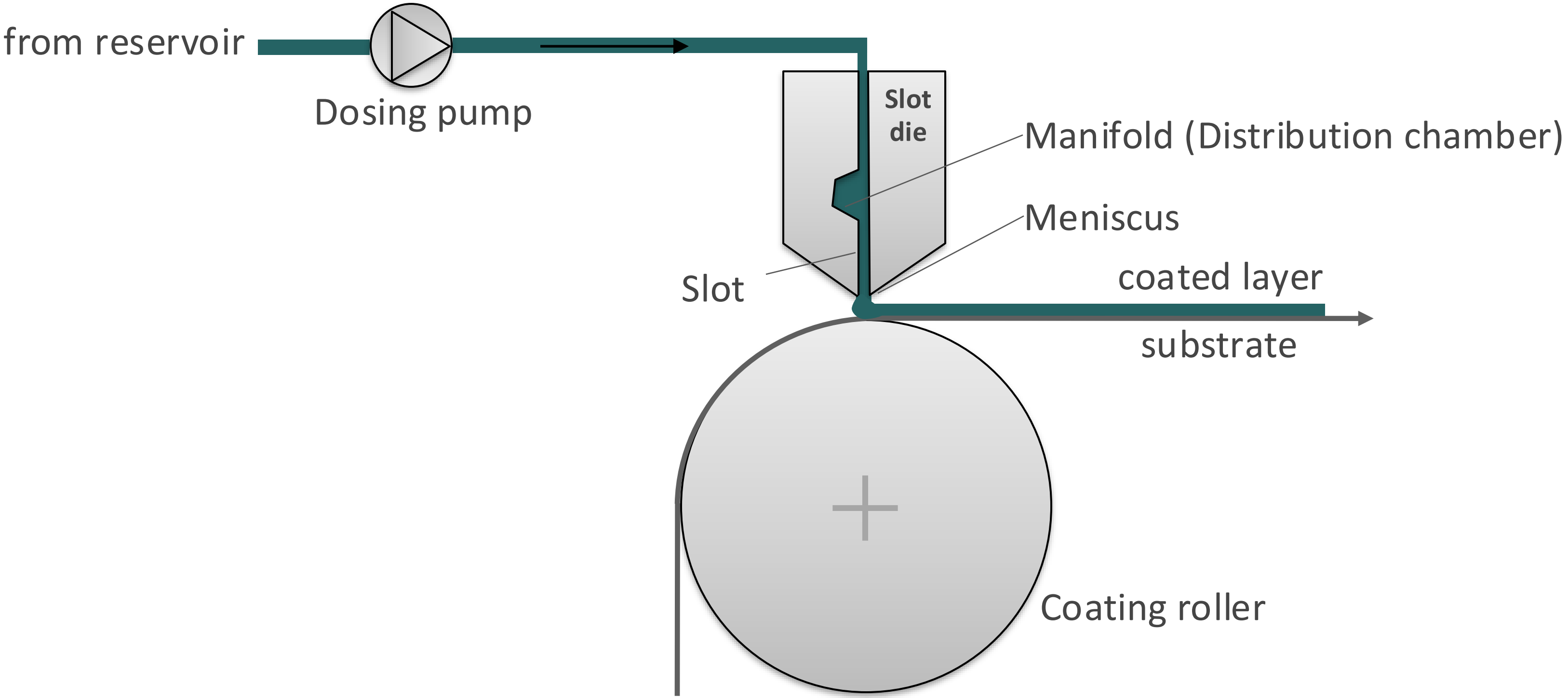
Basic principle

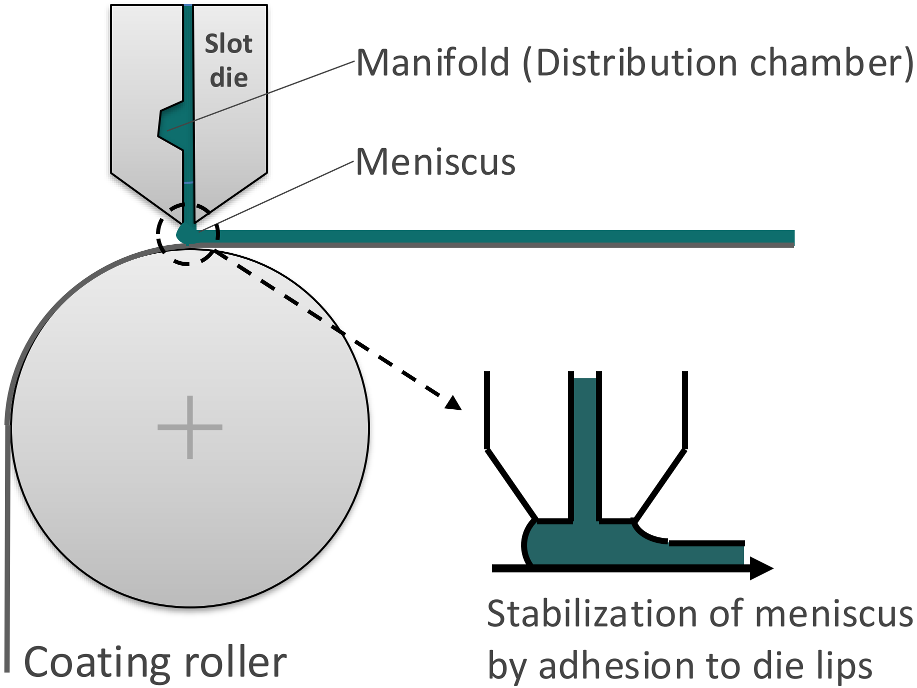


Basic principle

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

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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:

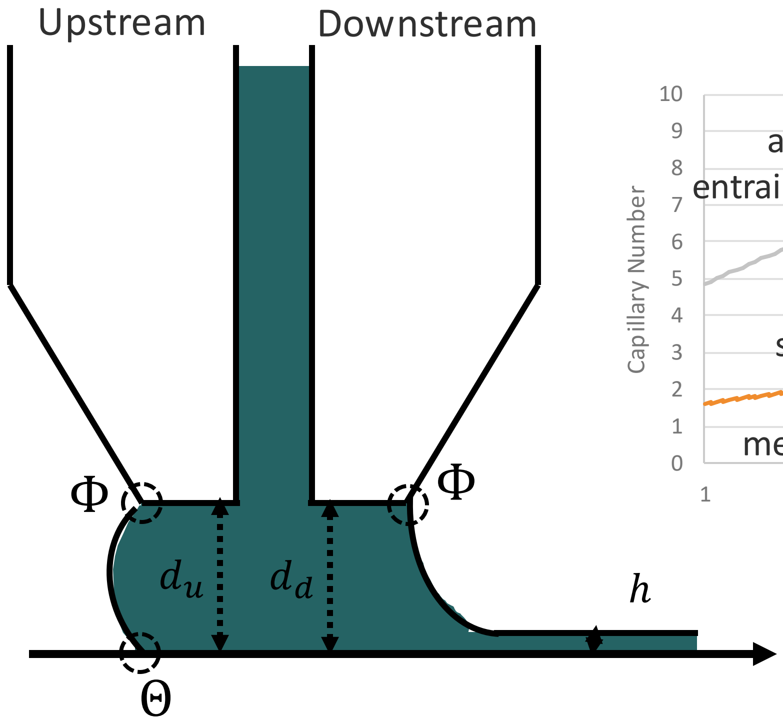
To describe the meniscus flow of a slot die means, to solve these differential equations for given boundary conditions.

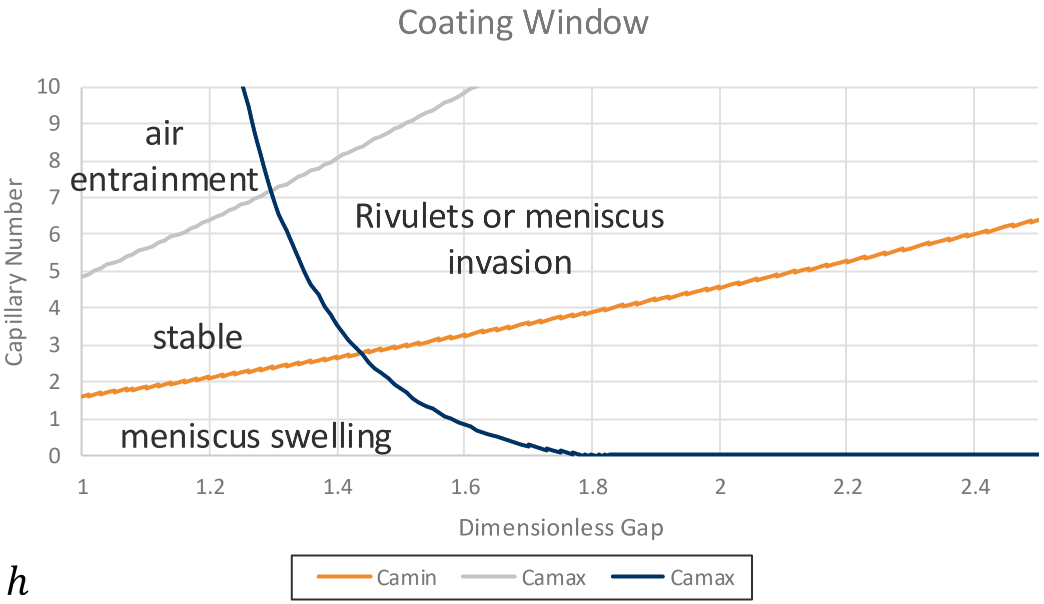
Can be done by appropriate computer programs.

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

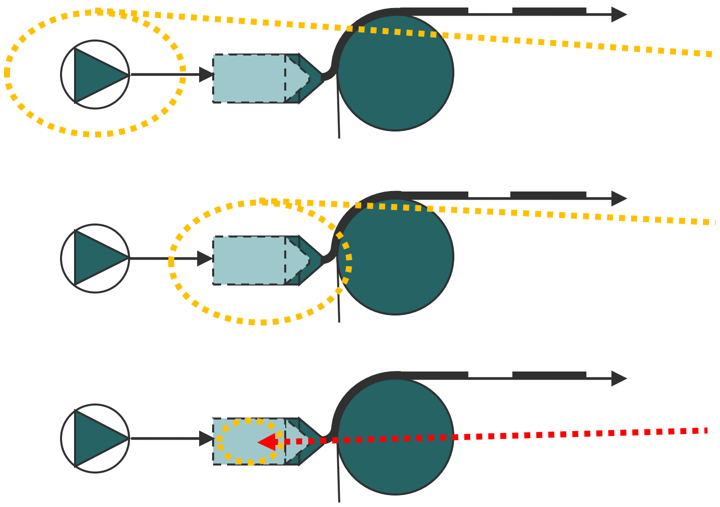
Navier-Stokes-equations (equations of motion for incompressible fluids, ρ = const)
Δ,∇= differential operators

Calculation of the meniscus stability





Standard techniques for intermittent coating



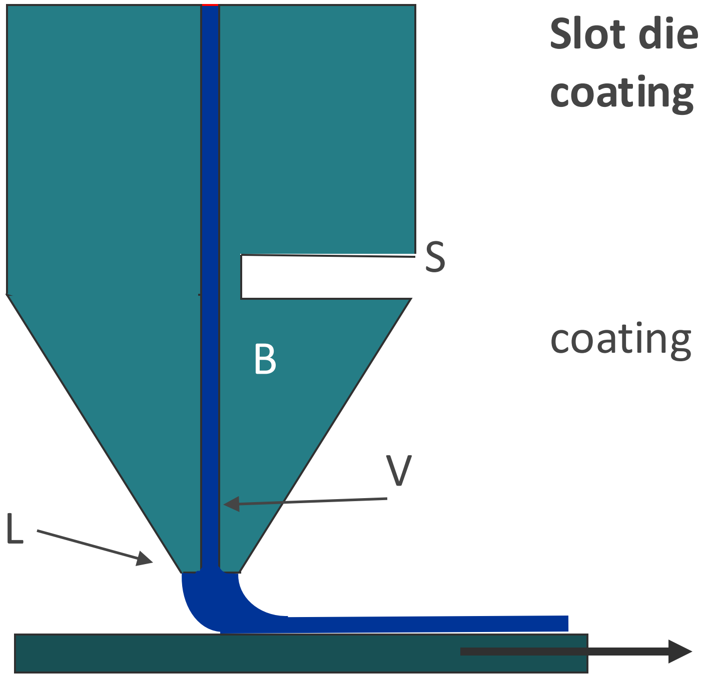
Pump:
stop – reverse – restart

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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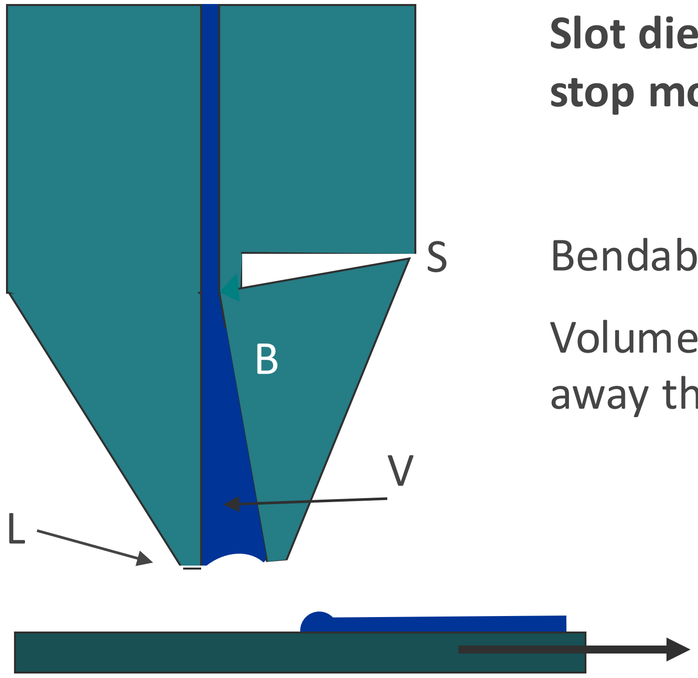
Structured coating – the switching slot die lip



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.

Drying technologies

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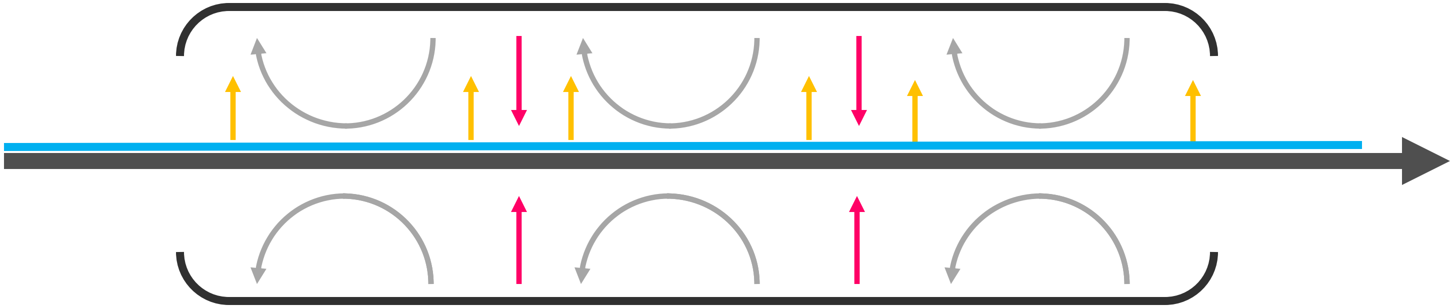
Introduction thermal drying – As general as possible(!?)



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

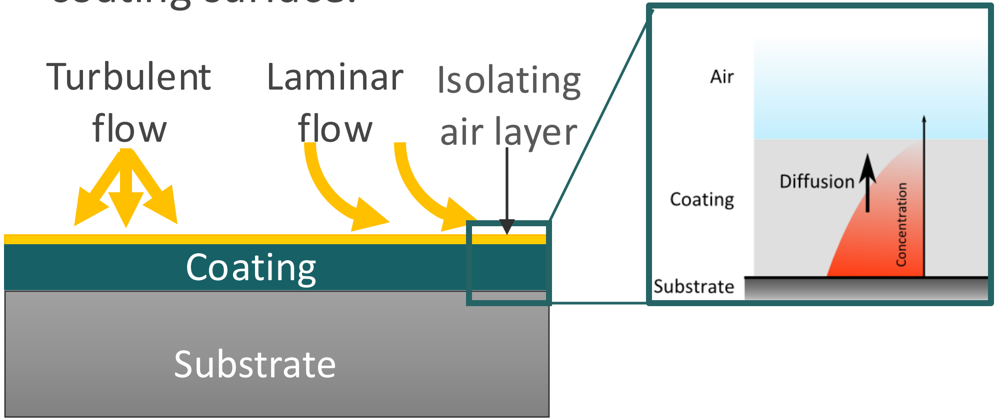
Substrate
Coating
Heat transfer
Evaporating solvent
Solvent vapor transfer

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.

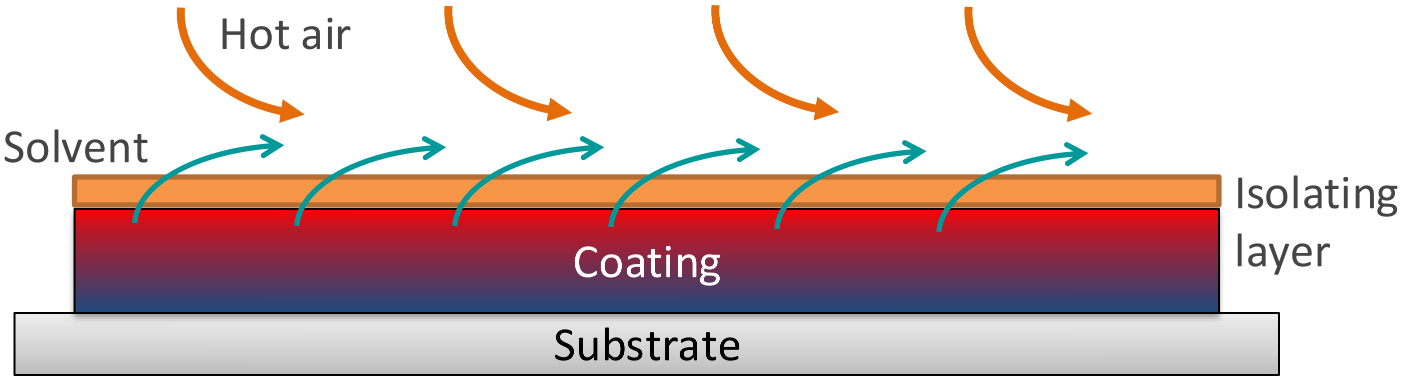


Usually there is a trade-off:

effective fast heat/mass transfer
or
gentle mild slow drying

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

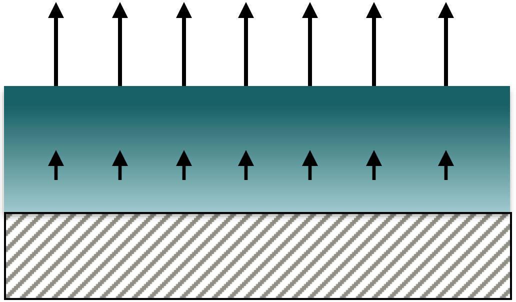
- ✓ Heating and vapor transport combined
- ✓ Bulk heating by thermal conductivity from surface
- ✓ Isolating layer to be overcome by air flow
- ✓ High air flow deteriorates surface
- ✓ Temperature easy to limit
- ✓ Slow



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

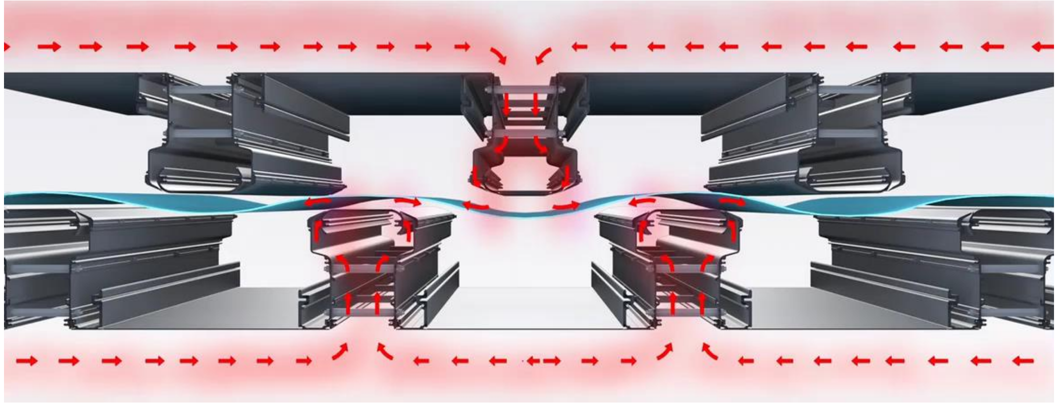
Industrial drying systems

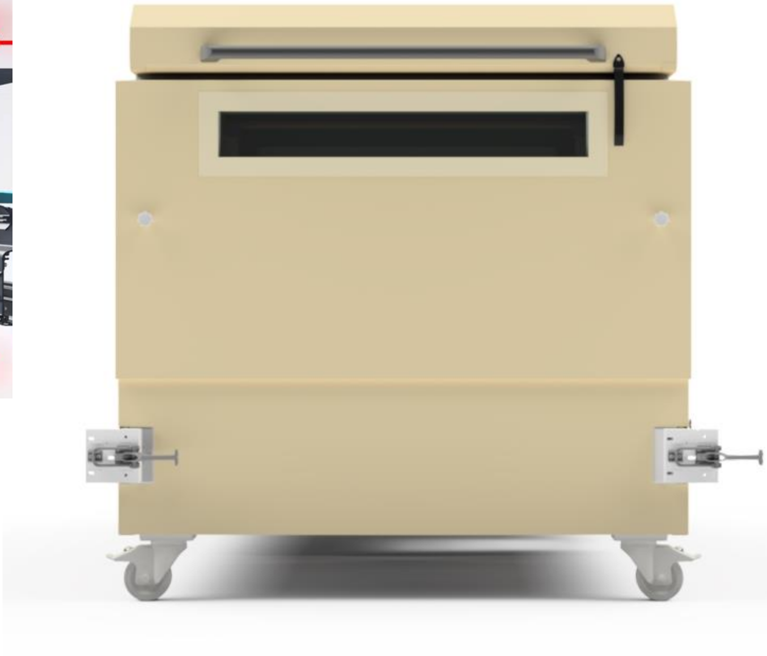
Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

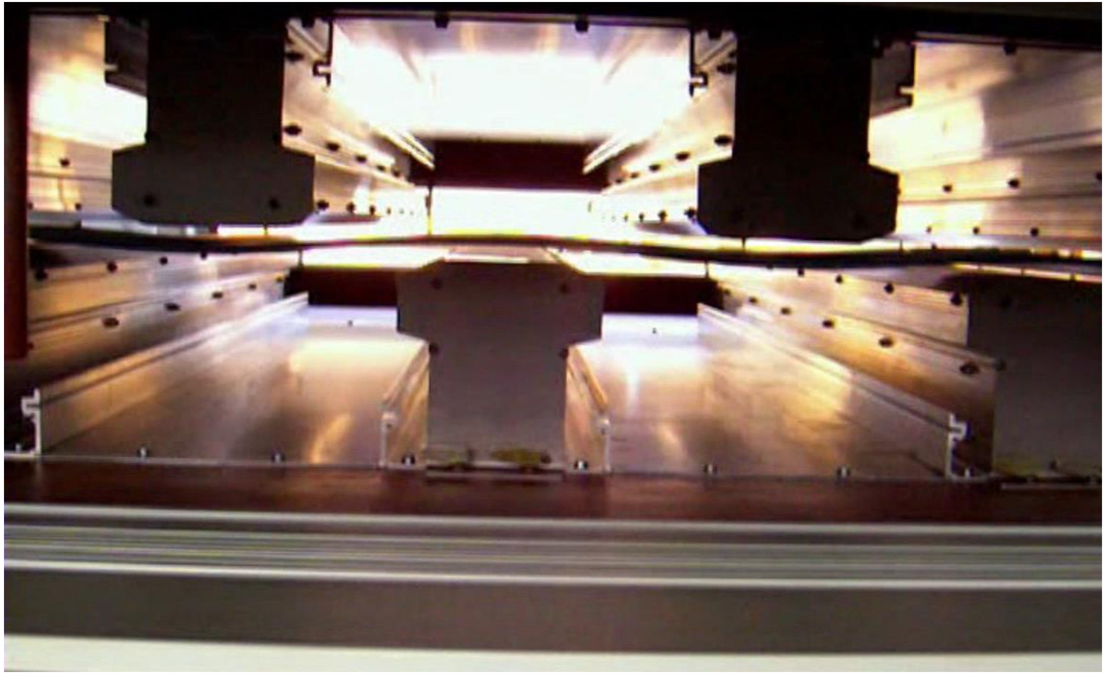
Drytec Click&Coat™ dryer prinziple





Drying topics – drying technologies: HighDry HD500

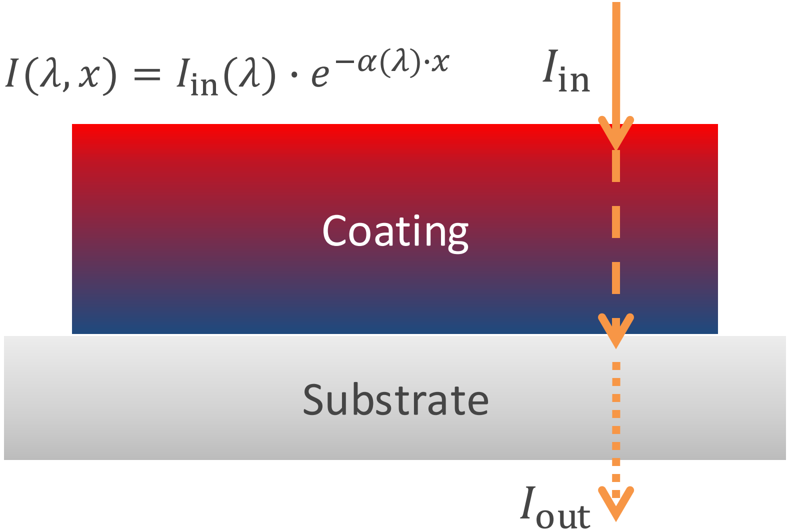
Web behaviour in a flowtation dryer



Press Button to show the video

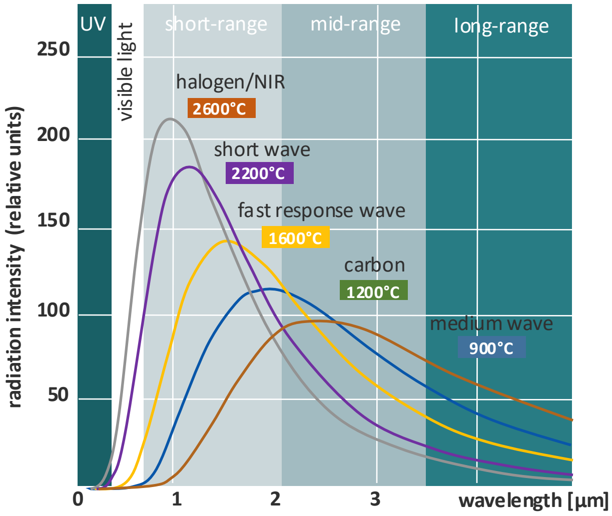
Basics mass + heat transfer: (N)IR technology

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



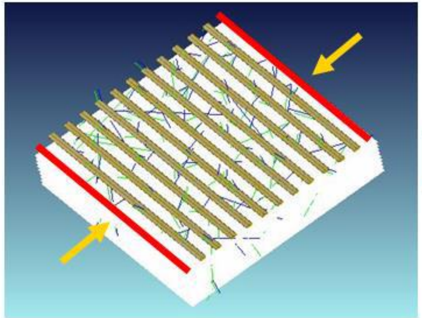
$I_{in}(\lambda)$ Intensity in
I_{out} Intensity out
$\alpha(\lambda)$ Absorption coefficient
d Layer thickness

High absorption | Optimum absorption | Low absorption



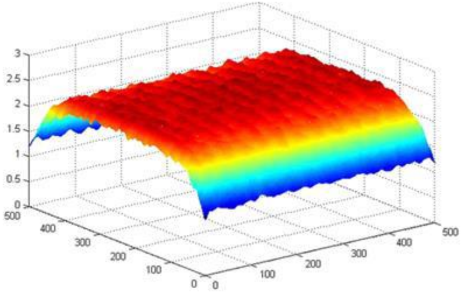
Relative intensity of radiators at different wavelengths

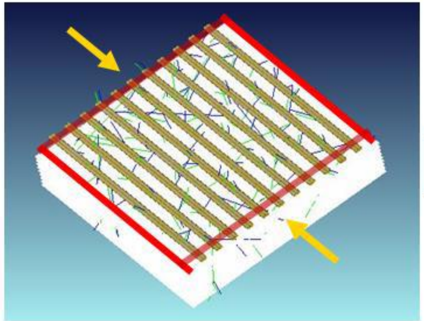
IR / NIR Drying – Infrared drying



Continuous process

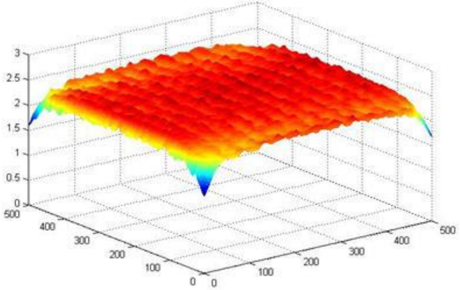
13 emitters, 2 types, 3 zones





Batch process

15 emitters, 3 types, 5 zones



Soucre: Heraeus Noblelight

Heraeus

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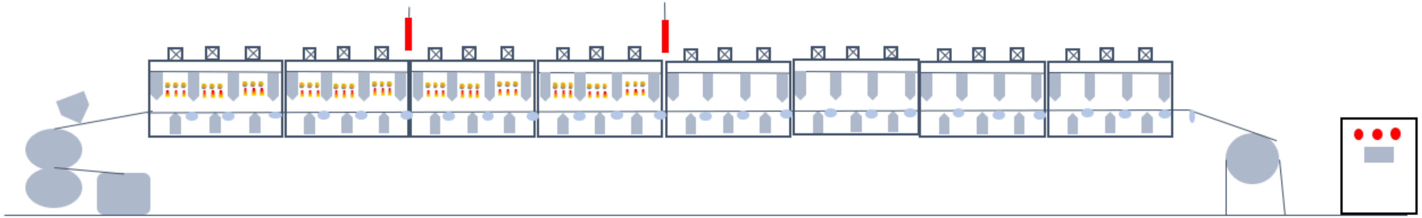
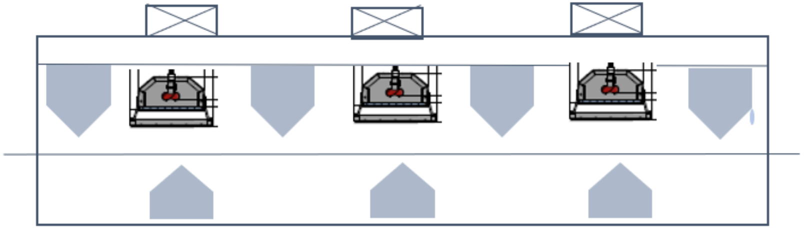
IR / NIR Drying – Infrared drying

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

6.

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

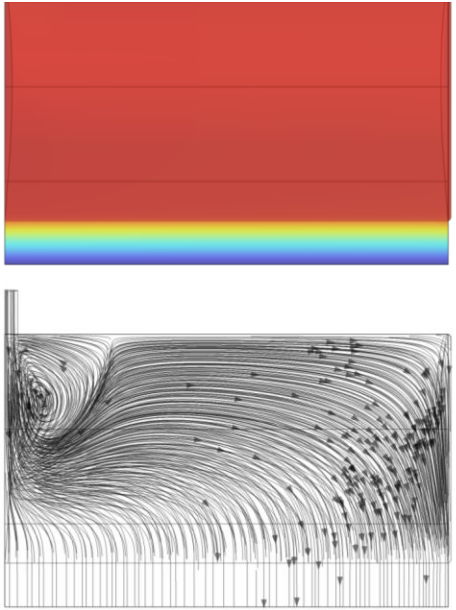
Name	Expression	Value	Description
W	0.8[mm]	8E-4 m	Slot gap
Hc	5[mm]	0.005 m	Inlet height
W_dd	1[mm]	0.001 m	Die width downstream
W_ud	1[mm]	0.001 m	Die width upstream
alpha_u	35[deg]	0.61087 rad	Upstream die angle
alpha_d	35[deg]	0.61087 rad	Downstream die angle
L_u	4.5[mm]	0.0045 m	Upstream length
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

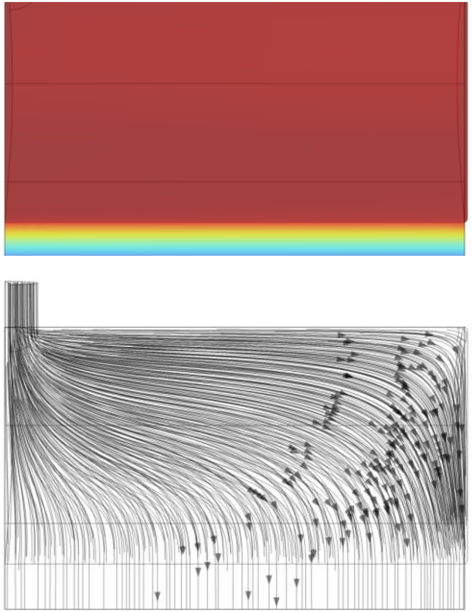
- Example for anode electrode coating
- Fluid data taken from real world (shear-thinning power law fluid)
- Process parameters for 90m/min 400µm coating and 300 mm width
- No „fancy" slot-die „just" Coatema standard

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

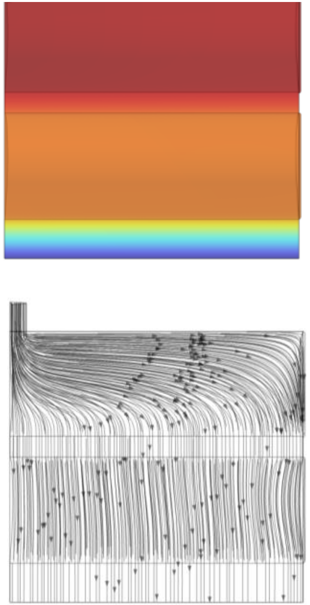
Single Chamber with too small inlet (4 mm)



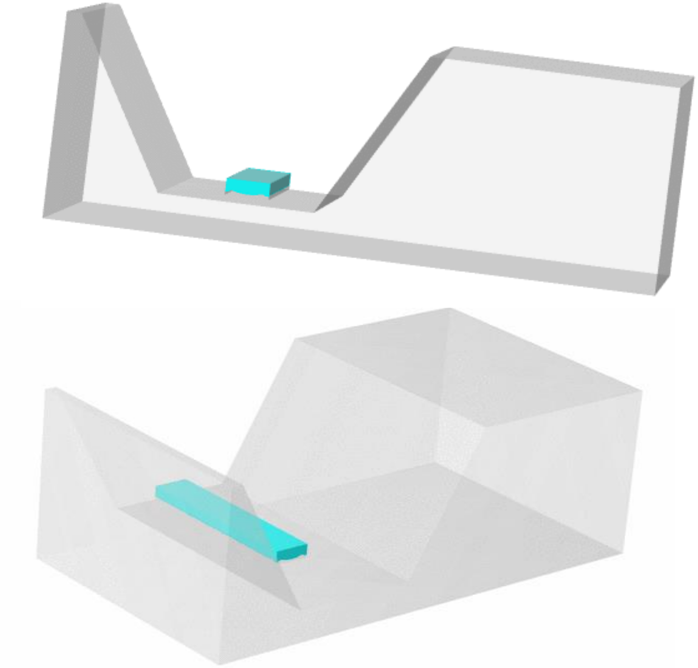
Single Chamber with correct chamber layout (10 mm inlet)

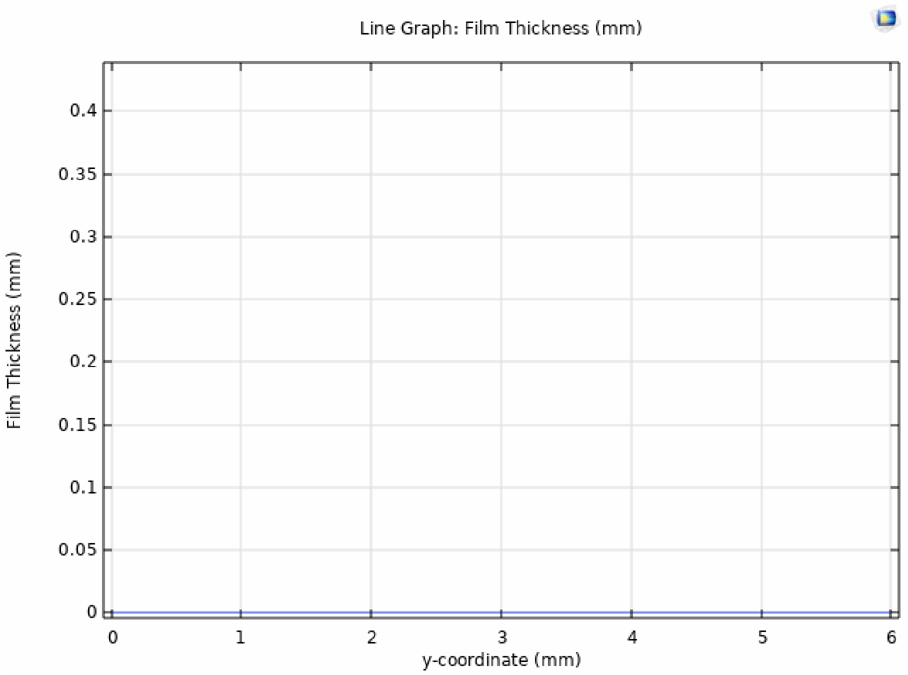


Dual chamber slot die (8 mm inlet same dead volume)



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





7.

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.

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Roseller Straße 4 ▪ 41539 Dormagen ▪ Germany
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