Full Scale Investigation of the Resulting Flow Field in Injection-compression Pultrusion with a Transparent Die

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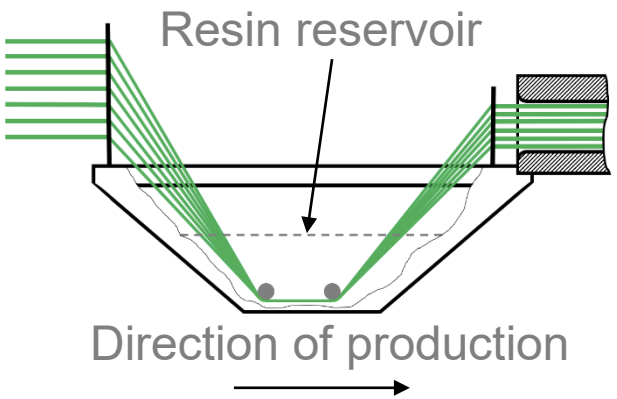
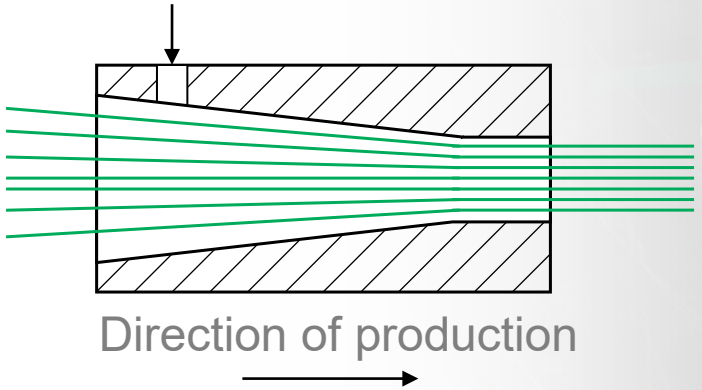
Injection boxes enable processing of highly reactive and sensitive resins

Open Bath



Injection box



Excess of resin
Undefined residence time

Need-oriented resin injection
Short and defined residence time

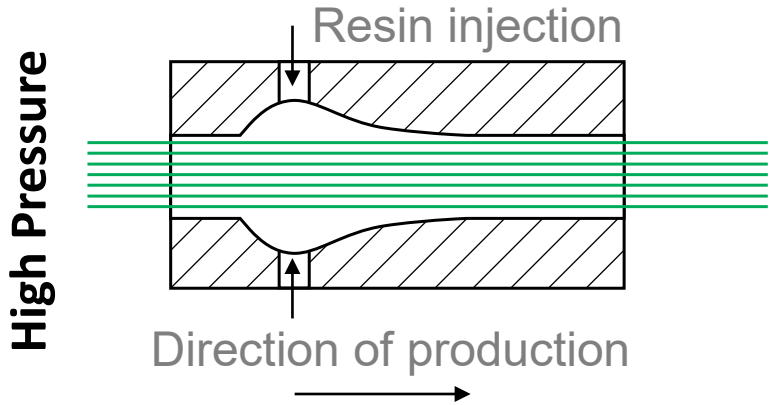
Strong emission of VOC
Large fluid surface area and strong circulation of resin

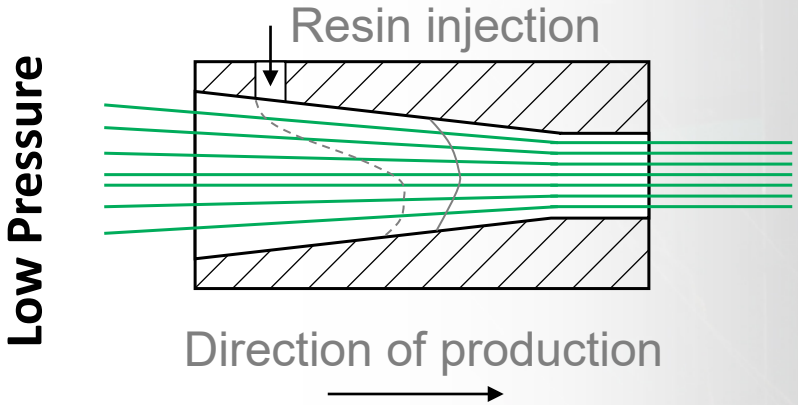
Less emissions of VOC
Small surface area and less circulation of resin

! Limitation of process speed
Emissions are regulated more rigorously

! The flow field within injection boxes is not understood properly
Design knowledge is mostly informal

Available concepts for realisation of injection boxes





- Fiber feed on profile contour
- Fiber impregnation with high pressure through thickness of profile cross-section
- Pressure build-up due to external pressure and gap between cavity wall and roving bundle

- Separated fiber feed & compression to profile contour
- Fiber impregnation through thickness of roving
- Dynamic pressure build up between converging rovings

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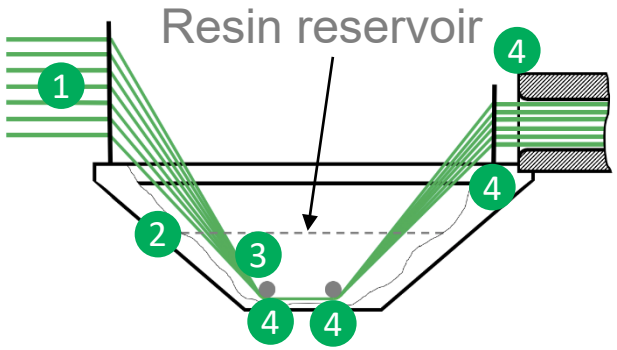
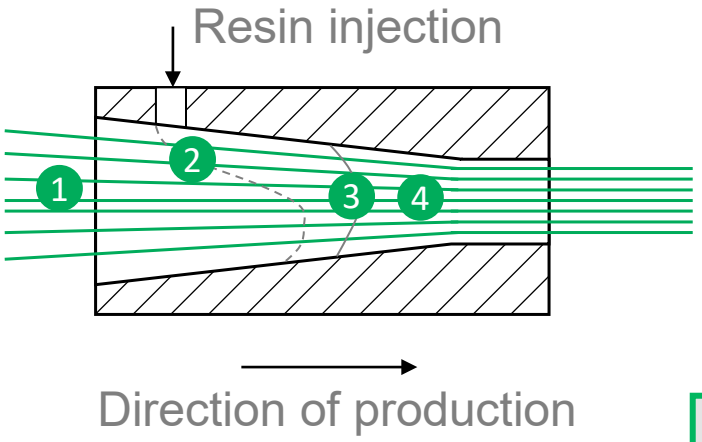
Low pressure design advantages:
Dosing equipment costs, sealing of the injection box, impregnation for higher production speeds and applicability for more complex profile shapes

Detailed comparison of fiber resin exposition in open baths and injection boxes





1. Dry rovings coming in separately
2. Initial contact of dry rovings with resin
3. Single rovings covered with resin
4. Dynamic pressure build up due to geometry

! Impregnation works based on the same mechanisms

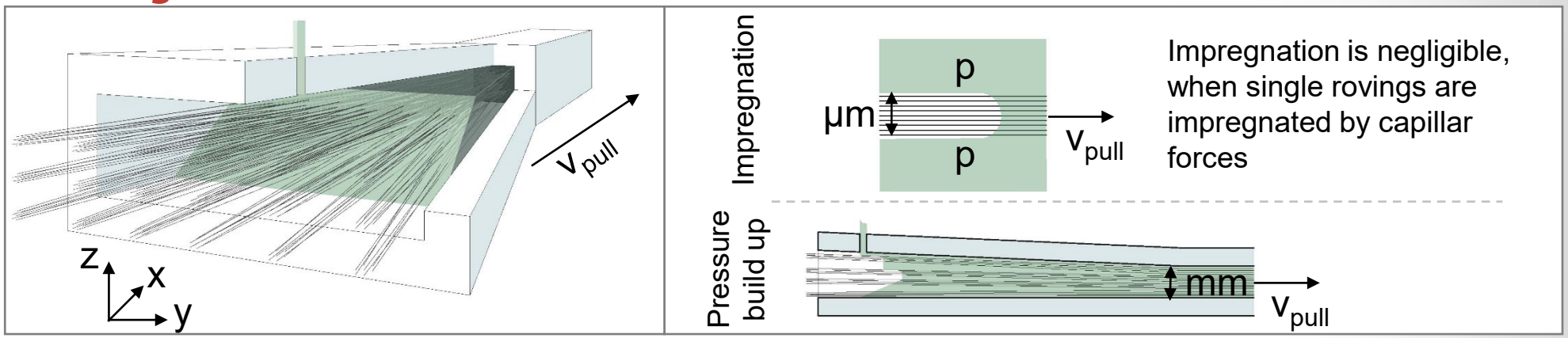
! Mechanisms in injection boxes are dense, inaccessible and need to be assessed deductively

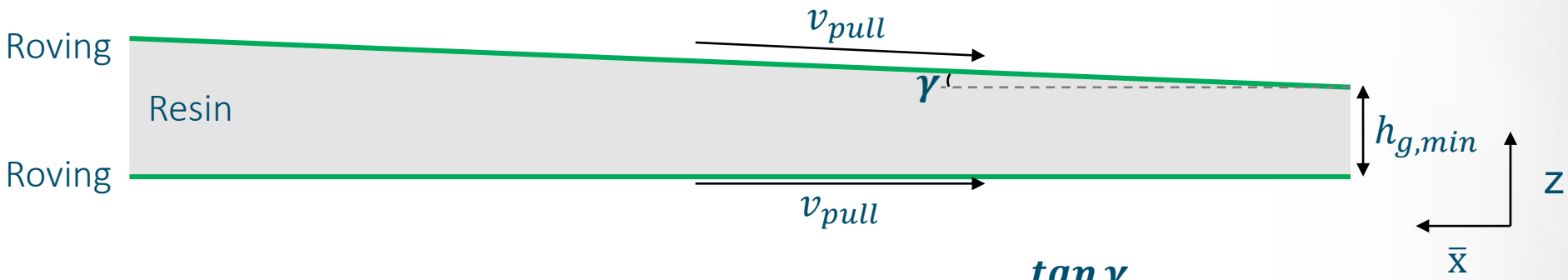
Where does impregnation actually happen and how does it effect other relevant parameters such as resin residence time ?

Agenda

- Motivation
- Discussion of pressure build up in injection boxes and relevant parameters for injection pultrusion
- Experimental setup with transparent injection boxes
- Results for essential process and material parameters
- Summary and Outlook

Locating impregnation and pressure build up in injection boxes

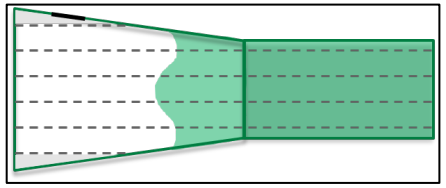




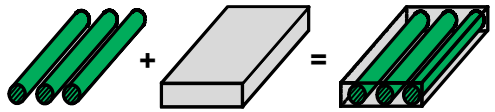
$$p(\bar{x}) = p_0 - 12\, v_{pull}\, \eta\, \frac{\tan\gamma}{\left(h_{g,min} + \bar{x}\tan\gamma\right)}$$

Gap Flow: $\frac{\partial p}{\partial \bar{x}} = \eta \frac{\partial^2 u}{\partial z^2}$ (Boundary conditions $u(z=0) = -u_\infty;\ u(z=h_s(x)) = -u_\infty$)

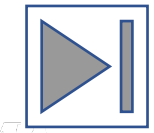
Parameters of injection pultrusion



- **Geometry**
  - Cross section
  - Cavity
    - Profile features
    - Opening angle vertical / horizontal
    - Fiber guidance
  - Injection point
    - Number
    - Position



- **Material**
  - Fiber
    - Fiber type
    - Fiber volume content
    - Capillary forces
  - Matrix
    - Viscosity
    - Capillary pressure



- **Process**
  - Control
    - Haul-off speed
  - Injection
    - Volume flow rate
    - Pressure

Digitally-retrofitted pultrusion machine at IKV

- Pultrusion machine from the 1980s (by Pultrex Ltd.)
- Completely integrated process data acquisition with National Instruments Software “LabView”
- Data is pushed directly on a server to enable live data analysis

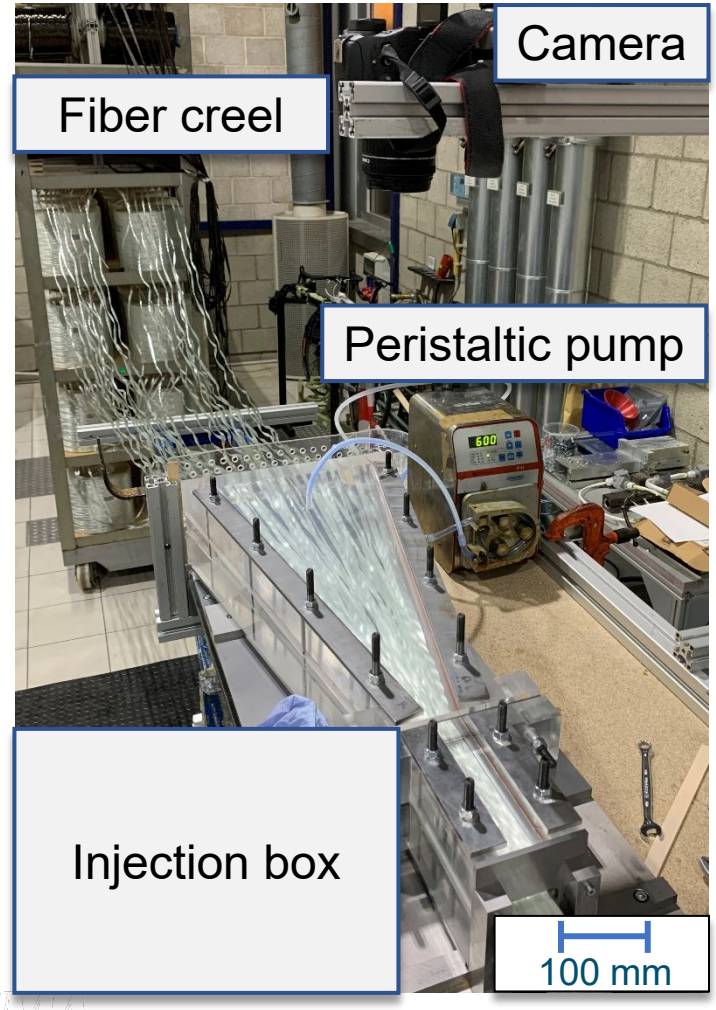
Configuration and parameters for initial investigations of the flow field in injection boxes

- Developed modular, transparent injection box enabling variation of geometry parameters
- Current configuration:
  - 31 x 4 mm rectangular cross section
  - Hor. Opening angle: 10.9°,1°
  - Ver. Opening angle (top): 2.5°
- Glass fibers: StarRov 090 by Johns Manville

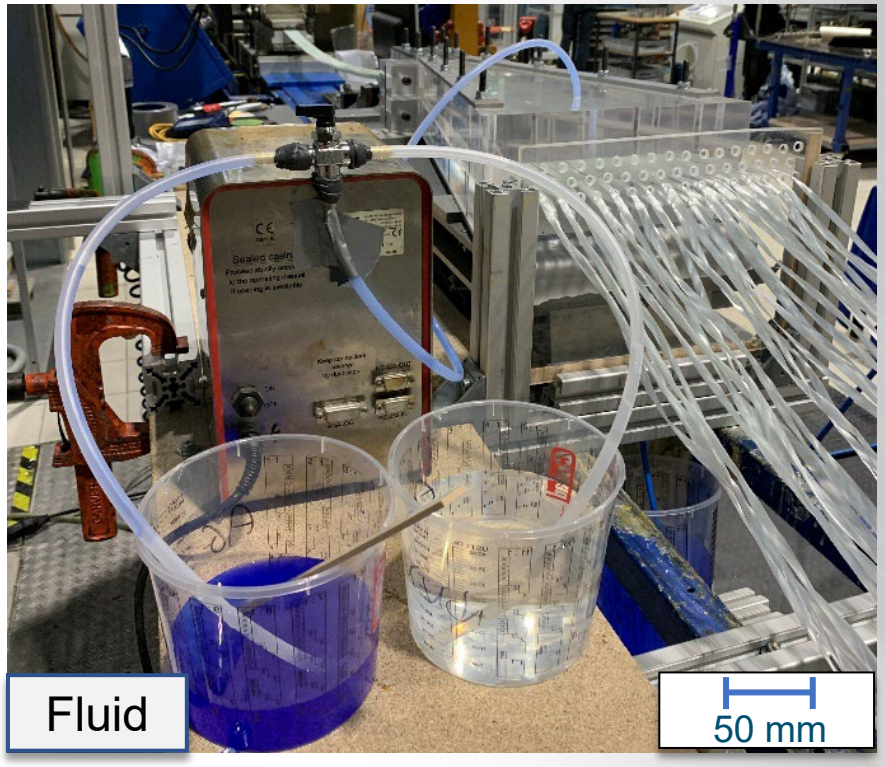
Variation of basic material and process parameters:

Haul-off speed [m/min]	Number of Rovings [-]	Theore-tical FVC [%]	Fluid [-]	Viscosity [mPa.s]
0.4	37	57.3	Sucrose Solution 5:3	120.5
1	40	61.9	Sucrose Solution 2:1	245.9
1.6	43	66.6		
2.2	46	71.2	Glycerin	1450

Experimental setup and measured values for trials with the transparent injection box

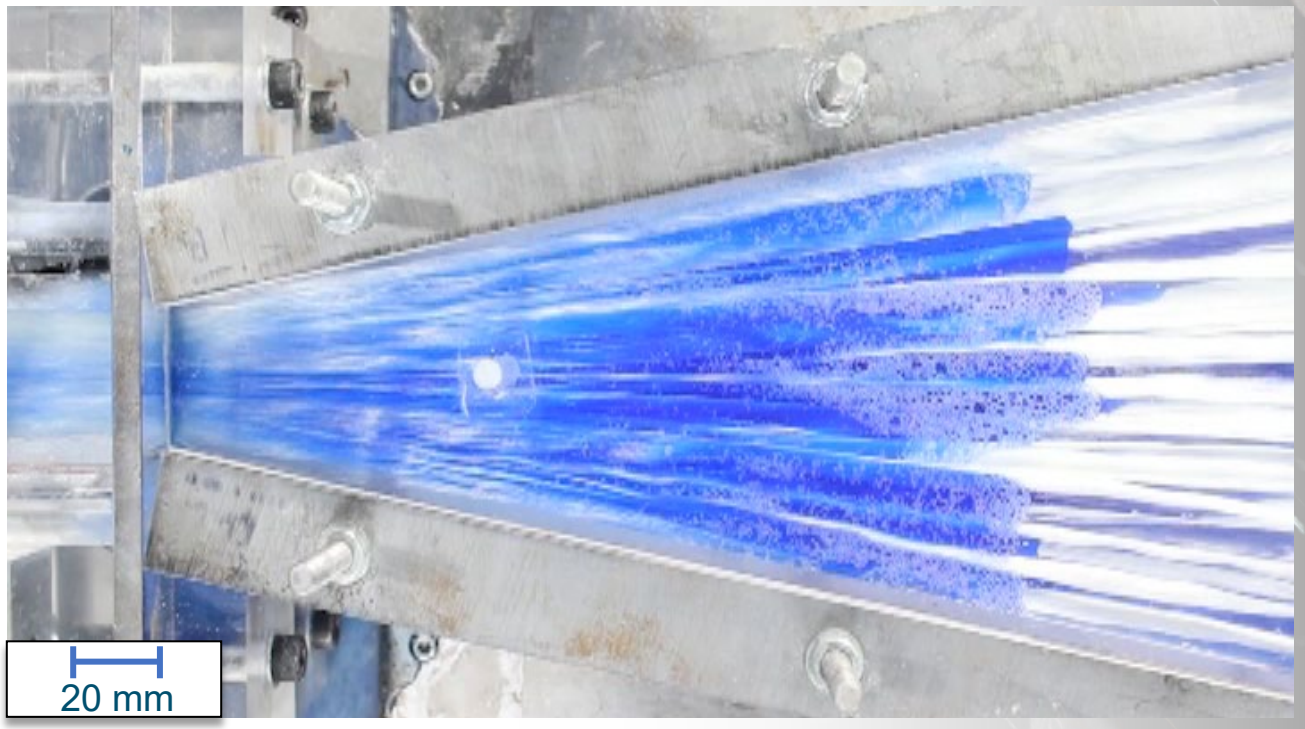


- Colored and uncolored fluids are used
- Distribution of fluid is analysed by image analysis
- Haul-off force is measured



Observation of flow behavior in transparent injection box

- Colored fluid increases contrast
- Flow front on lower levels exceeds flow front on top
- Air bubbles origin close to die entry, move against pulling direction and decrease in speed with distance to die
- Rovings are twisted and interact with other rovings
- The process is generally in a steady state, although the flow front varies significantly



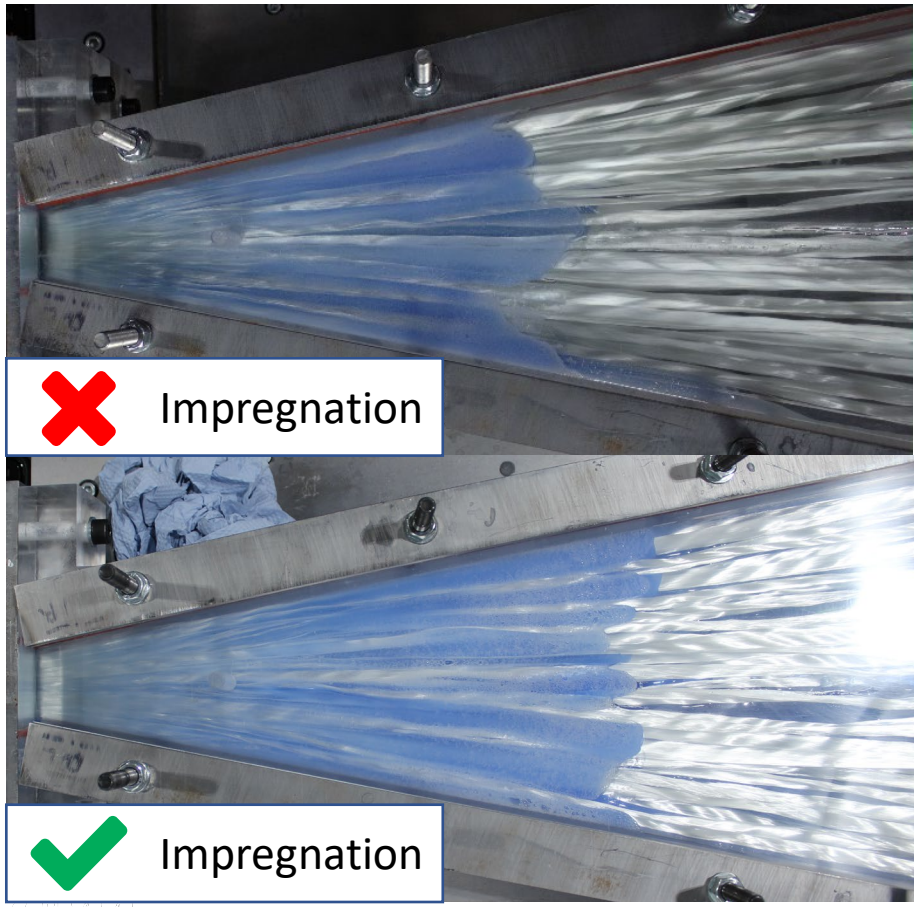
Visual comparison of trials at 1.6 m/min with Glycerin and Sucrose Solution

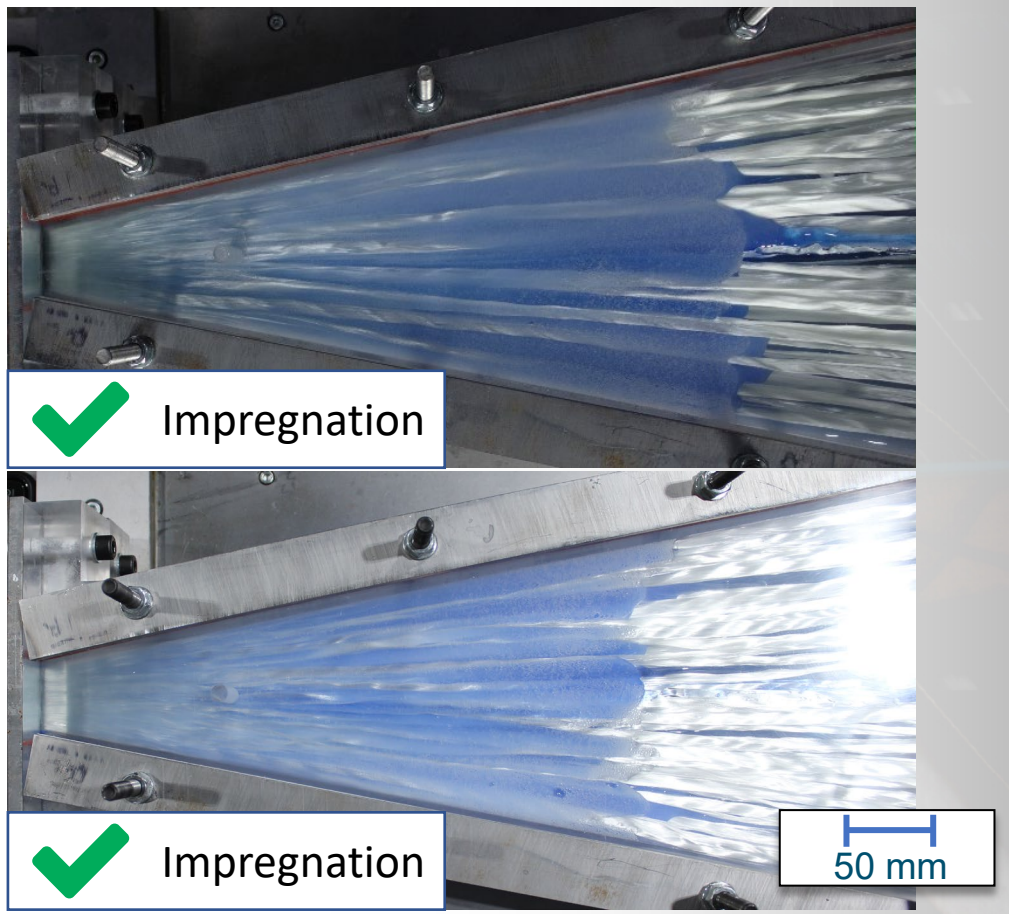
43 Rovings

46 Rovings

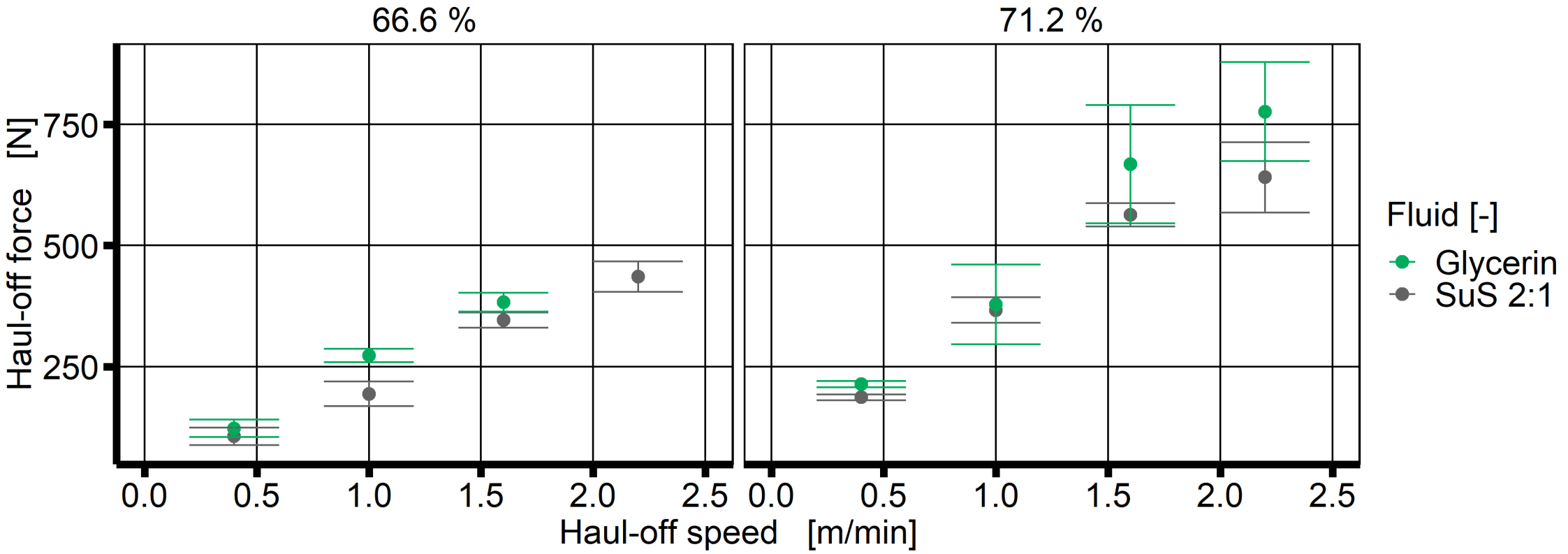
Glycerin

Sucrose Solution 2:1





Comparison of haul-off forces for fluids with different viscosities for different speeds



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The difference of forces for the two fluids does not represent the linear increase, that can be expected by the pressure build-up equation → Gaps between rovings are bigger and not evenly distributed

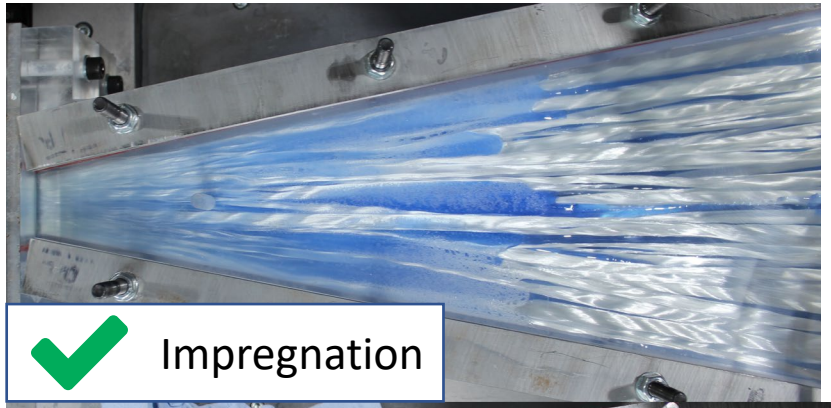
Visual comparison of backflow for varied horizontal opening angles at 1.6 m/min

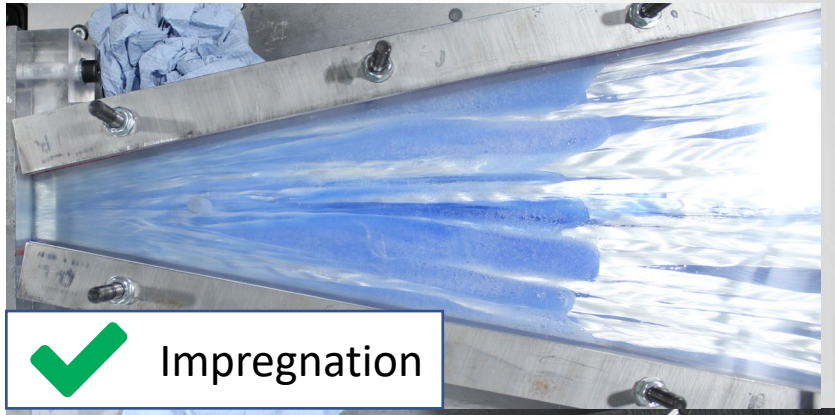
Sucrose solution 5:3 (120.5 mPas)

Sucrose solution 2:1 (245.9 mPas)

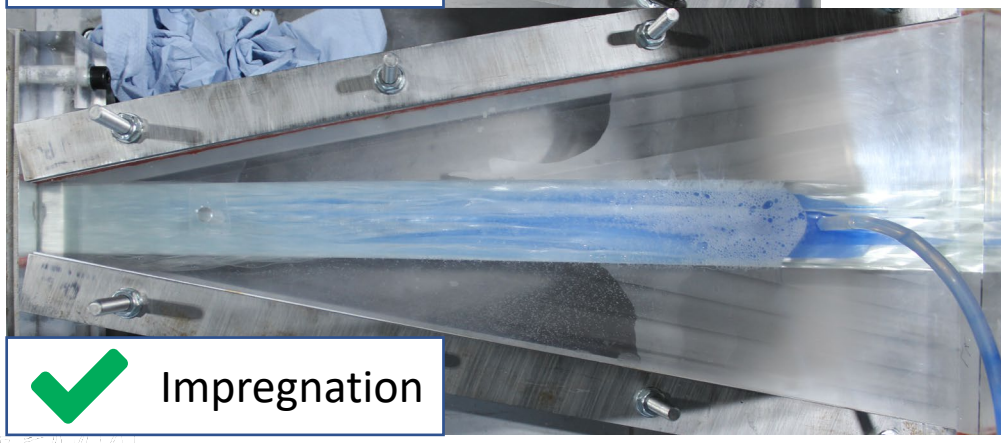
Horizontal opening angle

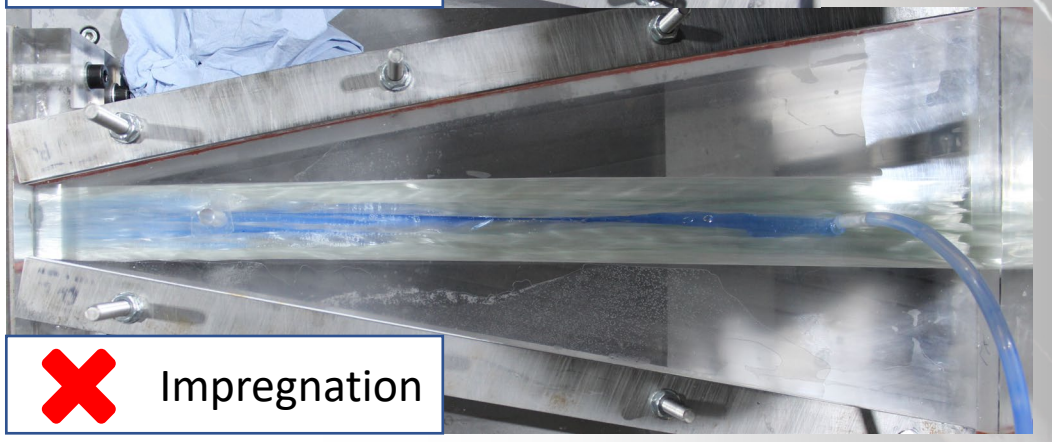
10.9°



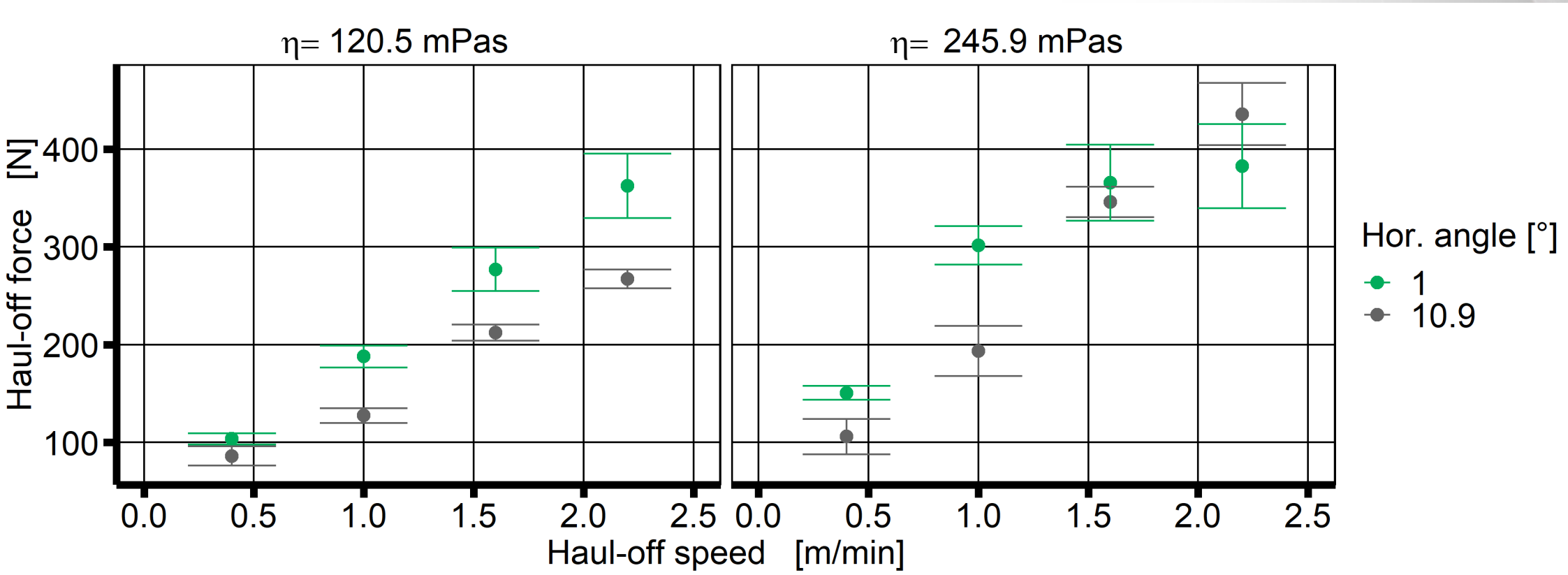


1°





Comparison of haul-off forces for varied horizontal opening angles



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Asymptotic development of haul-off forces with increasing haul-off speed for 245.9 mPas and 1° opening angles indicate deviations from the expected behavior and thereby incomplete impregnation

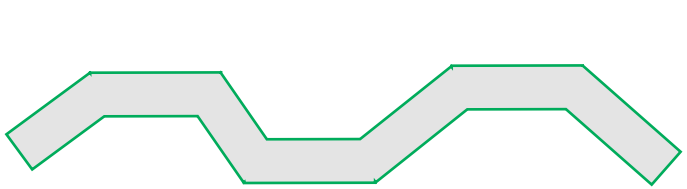
Summary

- Pressure build up in injection boxes correlates with resin viscosity, haul-off speed and a geometric function, that represents the converging geometry
- Investigations of the flow field in a transparent die offer a unique tool to investigate flow mechanisms in the injection box
- Comprehensive understanding can be developed without the limitations of successfully operating pultrusion processes
- Two examples for limitations of impregnation are presented:
  - High viscosities (> 1 Pa.s) lead to a rearrangement of rovings, so that single rovings are not covered with fluid and required exposure for impregnation increases
  - Small opening angles and higher viscosities lead to the same phenomena

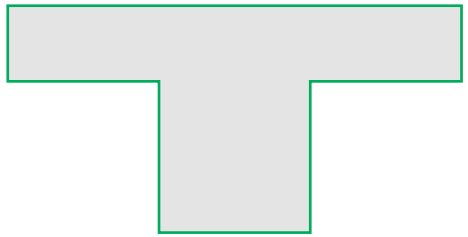
Outlook

The research project (21090N) of the Forschungsvereinigung Kunststoffverarbeitung is sponsored as part of the *"industrielle Gemeinschaftsforschung und -entwicklung (IGF)"* by the *German Bundesministerium für Wirtschaft und Energie (BMWi)* due to an enactment of the *German Bundestag* through the AiF.

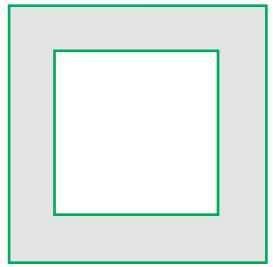
- Extensive investigations on the influence of material, process and geometric parameters on the flow field
- Development of an a priori description of flow in injection boxes to ensure impregnation and optimize pressure-build up and resin residence time
- Transparent injection boxes with more complex profile cross-sections in development:



Wave-like shape



T-Joint



Rectangular hollow tube

- Real pultrusion trials will be conducted to investigate the correlation of profile quality and injection box designs

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