MSc Program: AMT

Optimization of coating process in deformable roll coating systems by means of fluid flow simulation of non-Newtonian liquids

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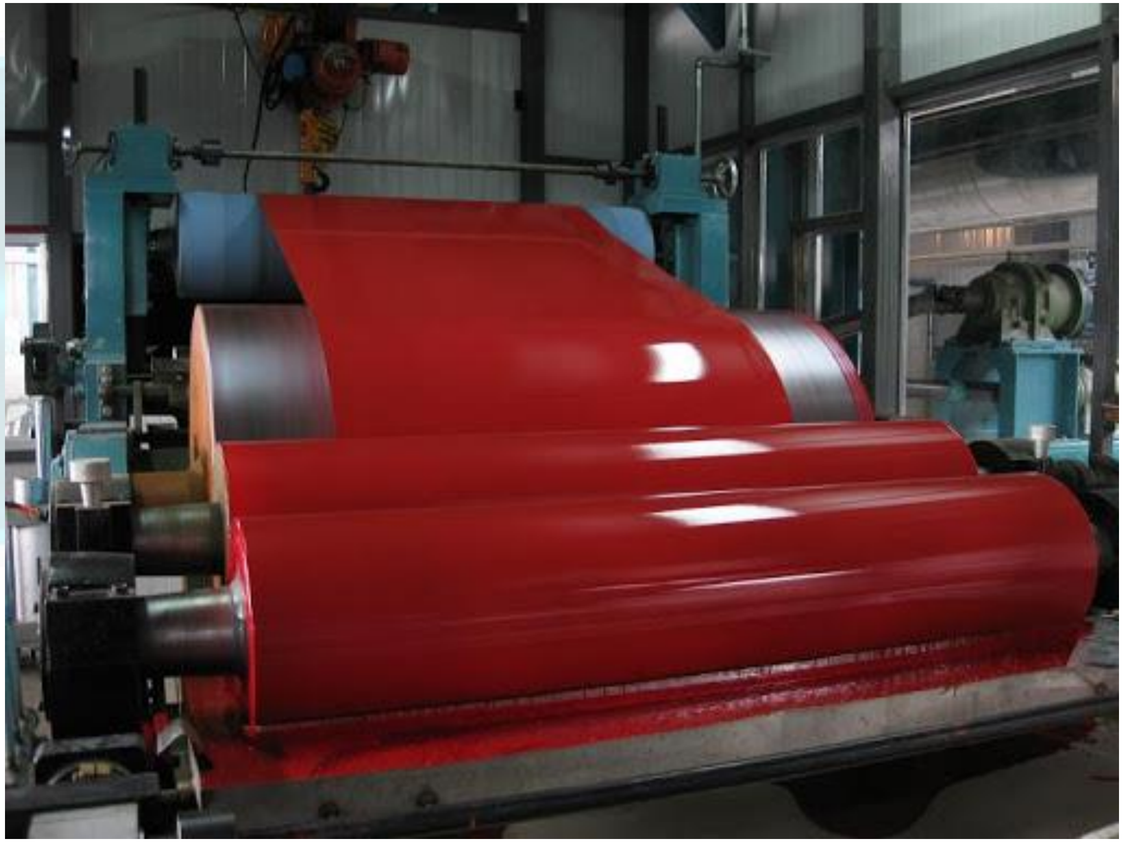
Content

Introduction: What's the process?

Roll coating is used to apply thin layers of substrate to the continuous moving web/sheet.

Our case:

Roll to roll non-Newtonian liquid paint coating on the steel sheets



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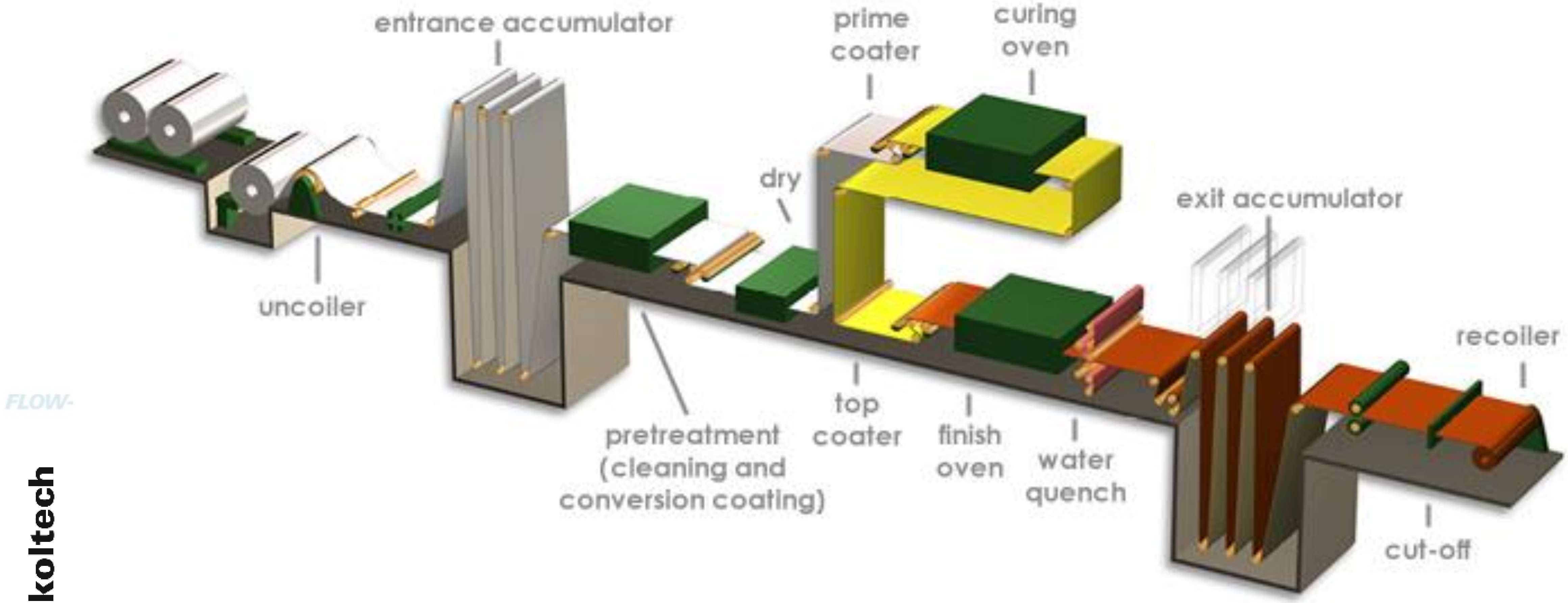
Introduction: What's the process?

On metallurgical plant steel sheets are painted from both sides



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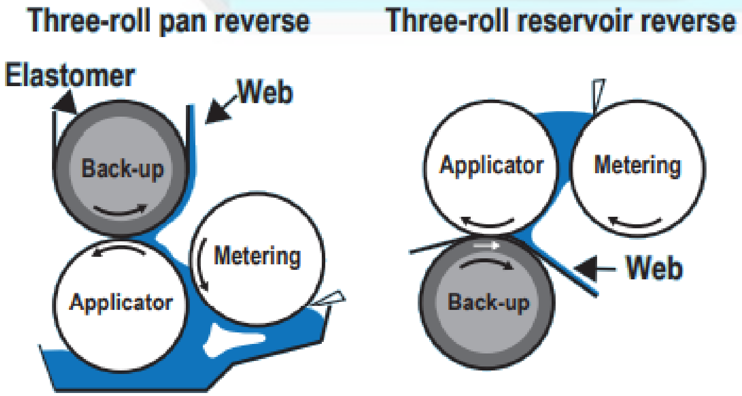
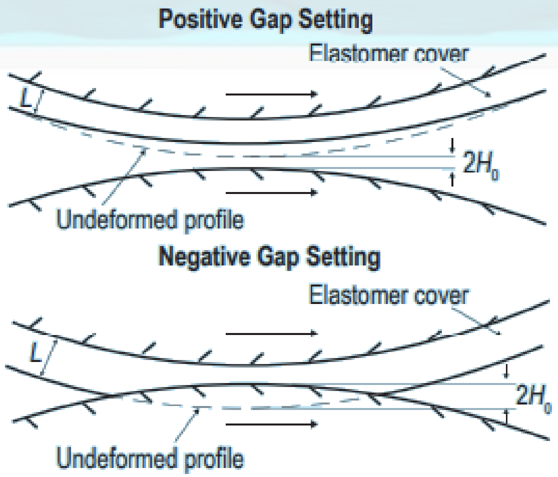
Introduction: Types of Roll coating systems

Way of differentiation	Types
Roll rotation	Forward/Reverse roll coating
Applicator roll material	Rigid/Deformable
Roll separation distance	Positive/Negative gap
Volume of coating at the nip	Flooded/Starving regime
Way of coating feeding	Nip/Pan fed





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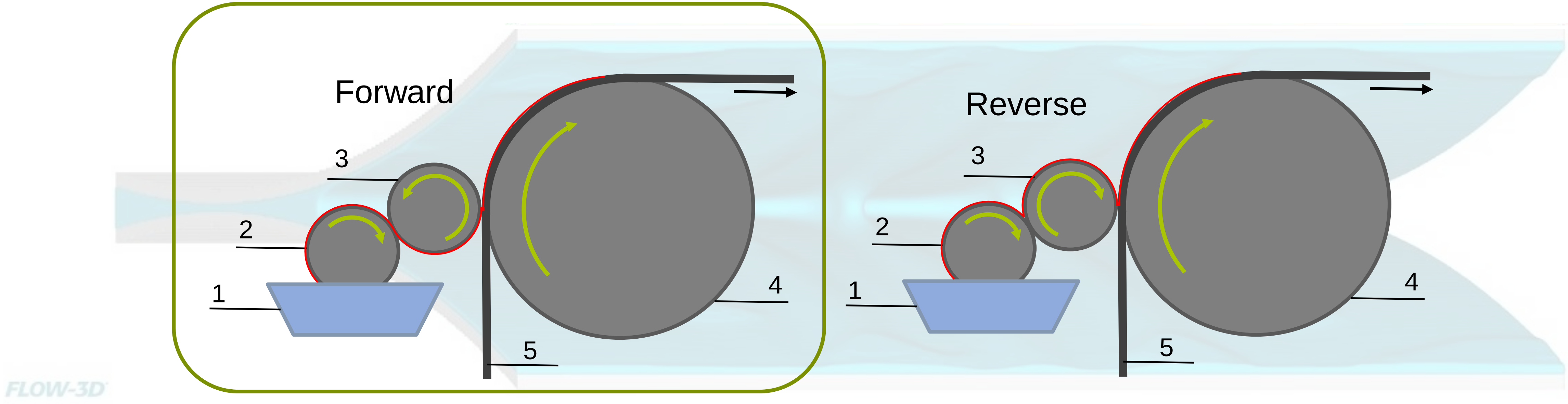
Introduction: NLMK System

Forward and reverse deformable roll coating operating at negative gap with the flooded nip and a pan fed system



1. Pan with paint
2. Steel pick-up roll (D = 270-300mm)
3. Rubber applicator roll (D = 270-310mm/ up to 30mm rubber)
4. Steel support roll (D = 800-1200 mm)
5. Steel sheet (0.3-2mm)

Steel sheet speed – 40-130 m/min
Roll speeds – up to 200% from sheet speed

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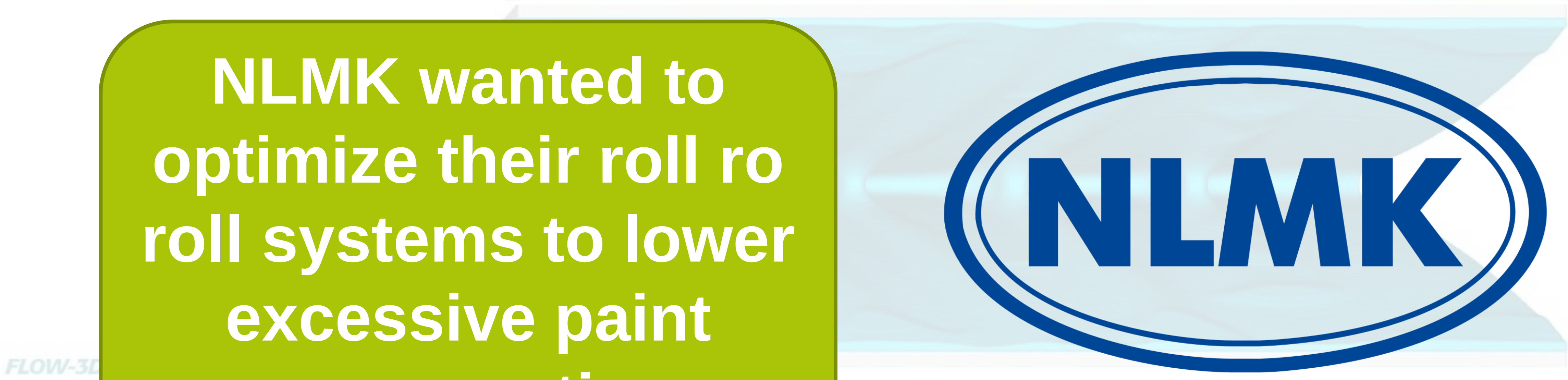
Research motivation

The project request came from NLMK company.



NLMK wanted to optimize their roll ro roll systems to lower excessive paint consumption

General problem

Now calibration of the coating systems are **performed manually**.

Extra set up time and **extra consumption** of the expensive coating material.

Coating parameters might **not be set precisely**

Coating unnecessary **overspending**

Up to **50 mil**. Rub. p.y.

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Research gaps and questions

Gaps:

- **Focus**
  Almost no research that would deeply and mainly focus on the thickness parameter in various systems and setups
- **Scalability**
  Few industrial application research performed
- **Optimization**
  No research on the optimization of the process

Questions:

- What it is and how it was done before?
  What method and models we should choose to solve our problem?
- What parameters affect the paint thickness and how?
- How to set up a model to get scalable results?
- Specifically, how roll speeds and distance between them/applicator force affect the thickness?

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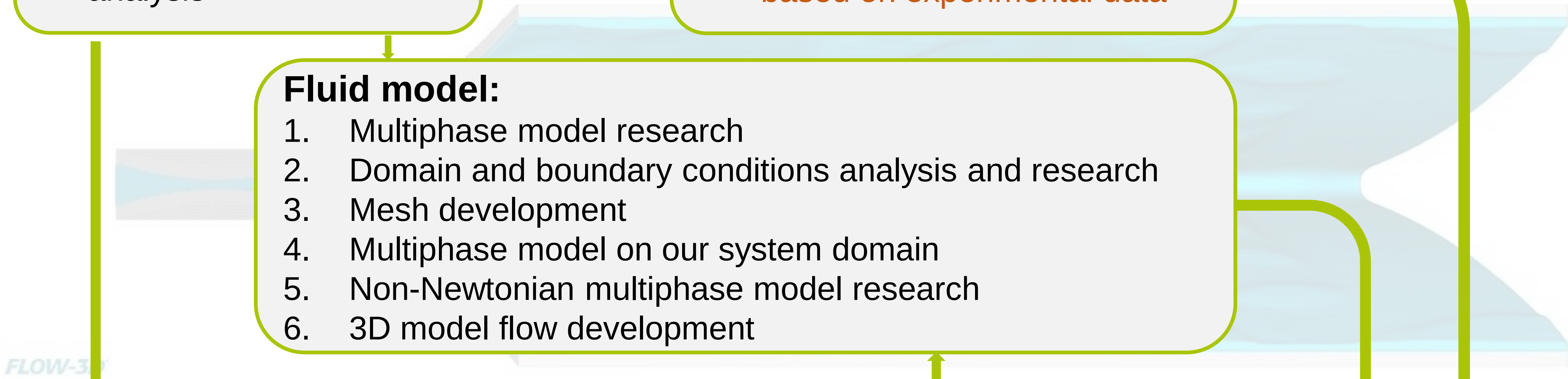
Aim and Objectives

Aim: The foundation of the roll coating process recommendation system to be used in industrial application that would optimize the processes on the plant

Objectives:

1. Development of the numerical coupled model of the deformable coating process
2. Obtaining data for the thickness measurements for different parameters of the model such as roll speeds and distance between the rolls/force of the applicator roll
3. Maintain the scalability factor for the methods used in the research

Steps towards the goal



- Literatue review
- Our system analysis
- Planning and methods analysis

Mechanical model:

1. Simple model implementation
2. Elastomer model development based on experimental data

Fluid model:

1. Multiphase model research
2. Domain and boundary conditions analysis and research
3. Mesh development
4. Multiphase model on our system domain
5. Non-Newtonian multiphase model research
6. 3D model flow development

Scalability and automation:

1. Ansys script techniques research
2. Development of the simple thickness measurement script
3. Development of the script for the parametrization run to obtain results for many parameters

Coupled model
development, data generation, validation and verification

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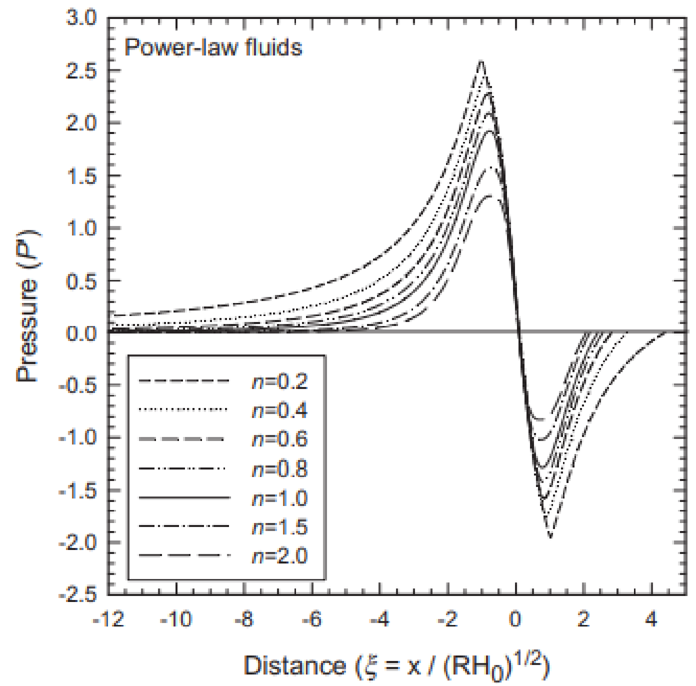
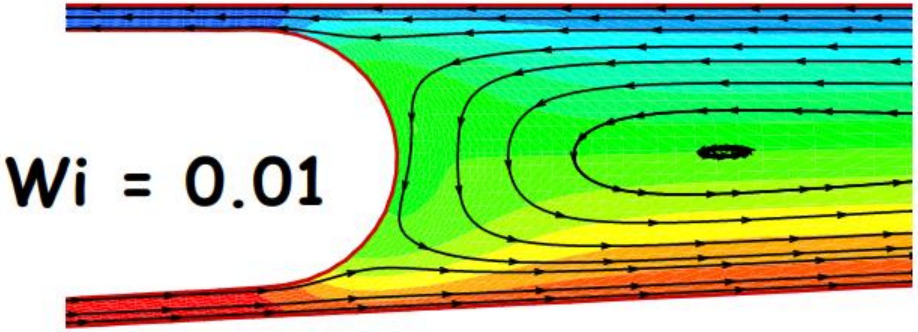
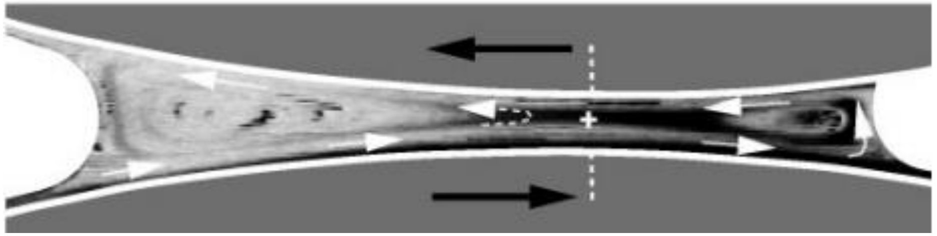
Literature Review

- Studies on roll coatings with non-Newtonian fluids
- Coating instabilities
- Experimental studies
- Theoretical studies
- Industry oriented studies
- Main authors in the field (Coyle, D.J., Scriven, L.E., Benkreira, H., Zahid, M)
- Ansys documentation



FLOW-3D





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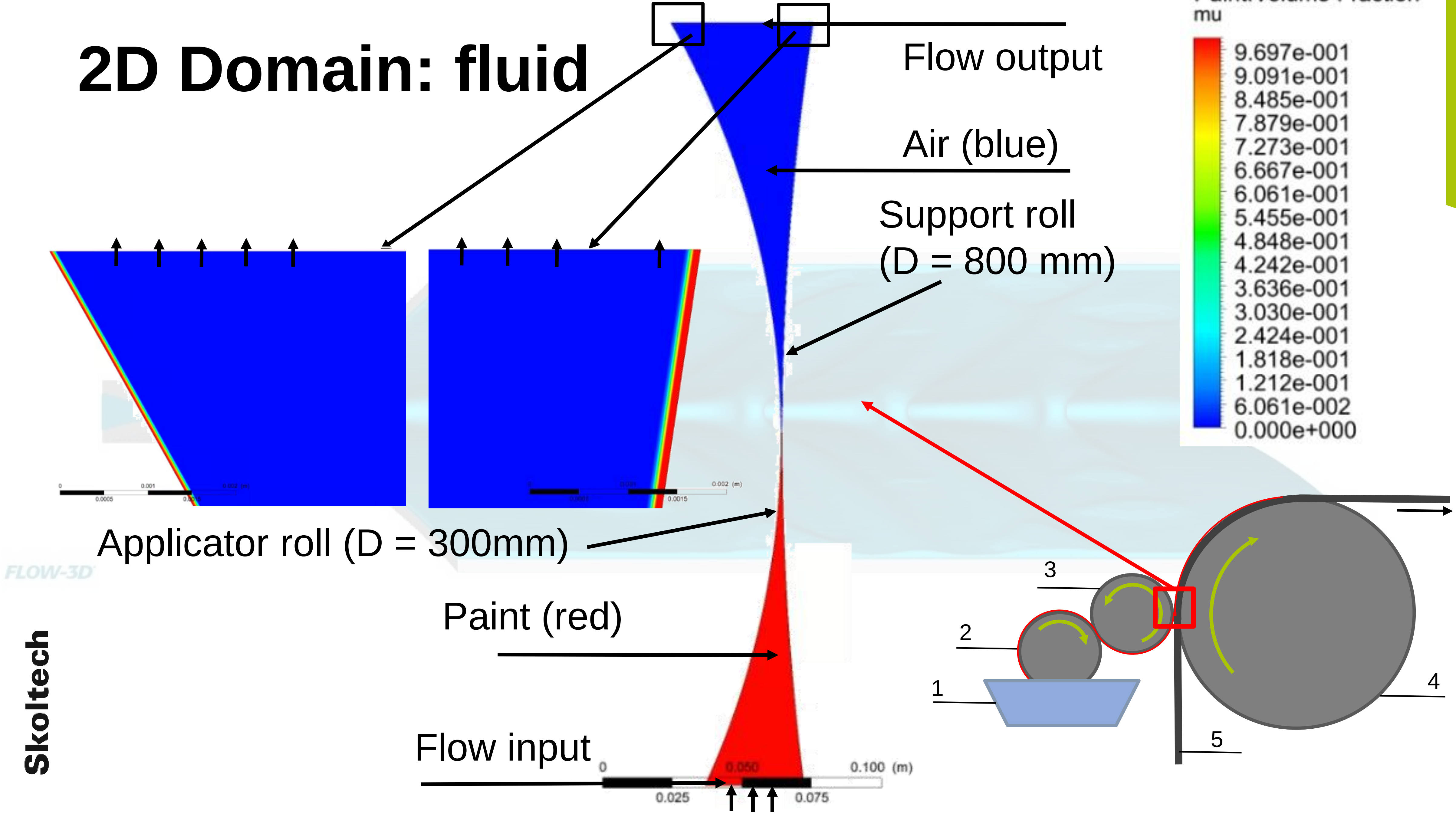
Methodology

Numerical model DevOp

- Mechanical model
  (Ansys Mechanical, pSeven)
- Fluid model (Ansys Fluent)
- Non-Newtonian model parameters
  (Maple + Python data analysis)
- Coupled Model (Ansys)
- Result analysis (Python/ Excel)

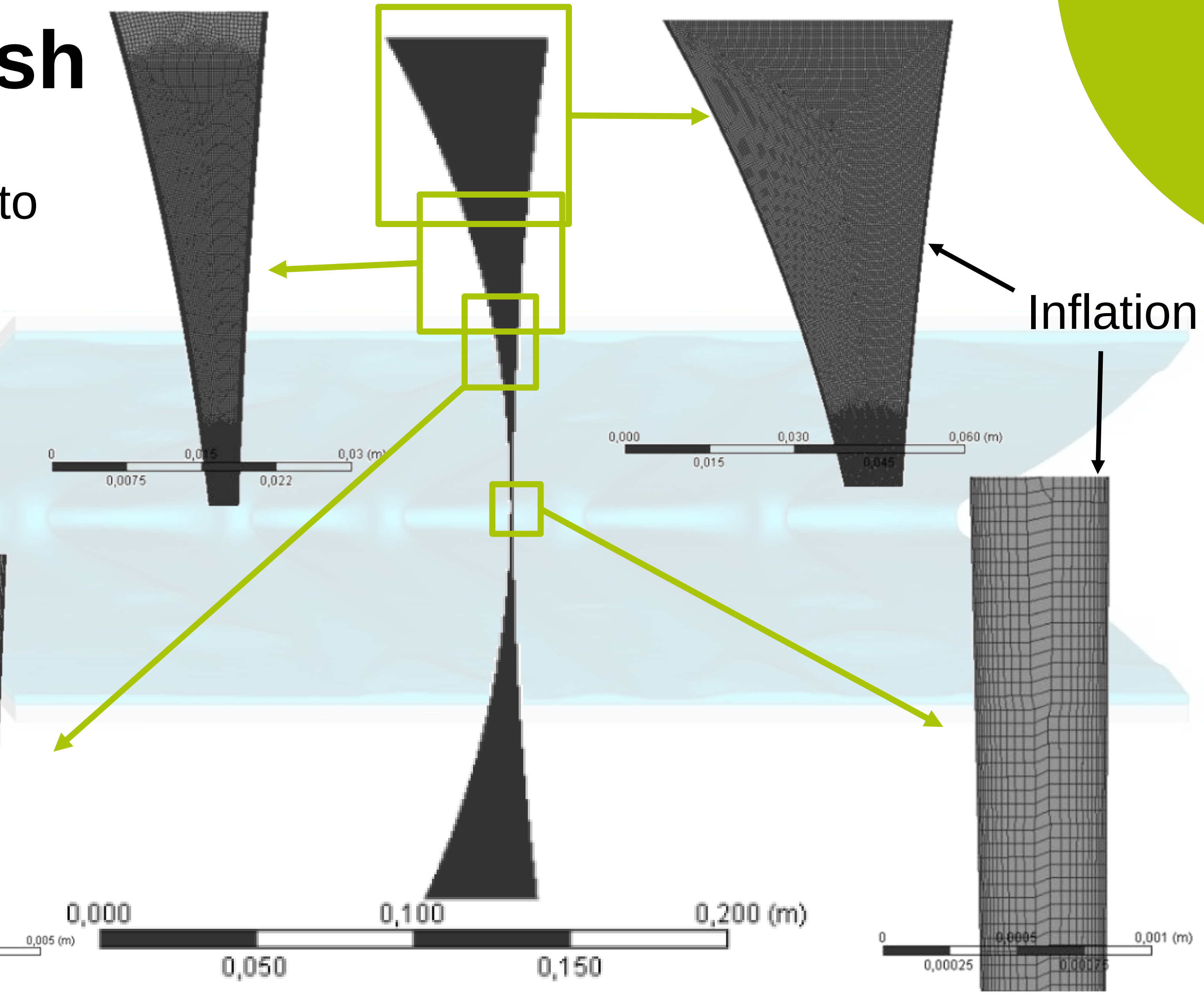
2D Domain: fluid

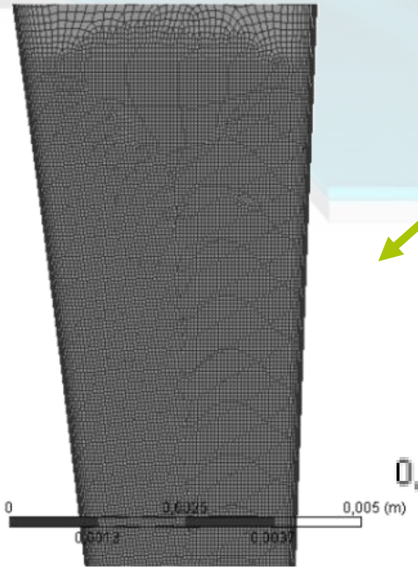


2D fluid mesh

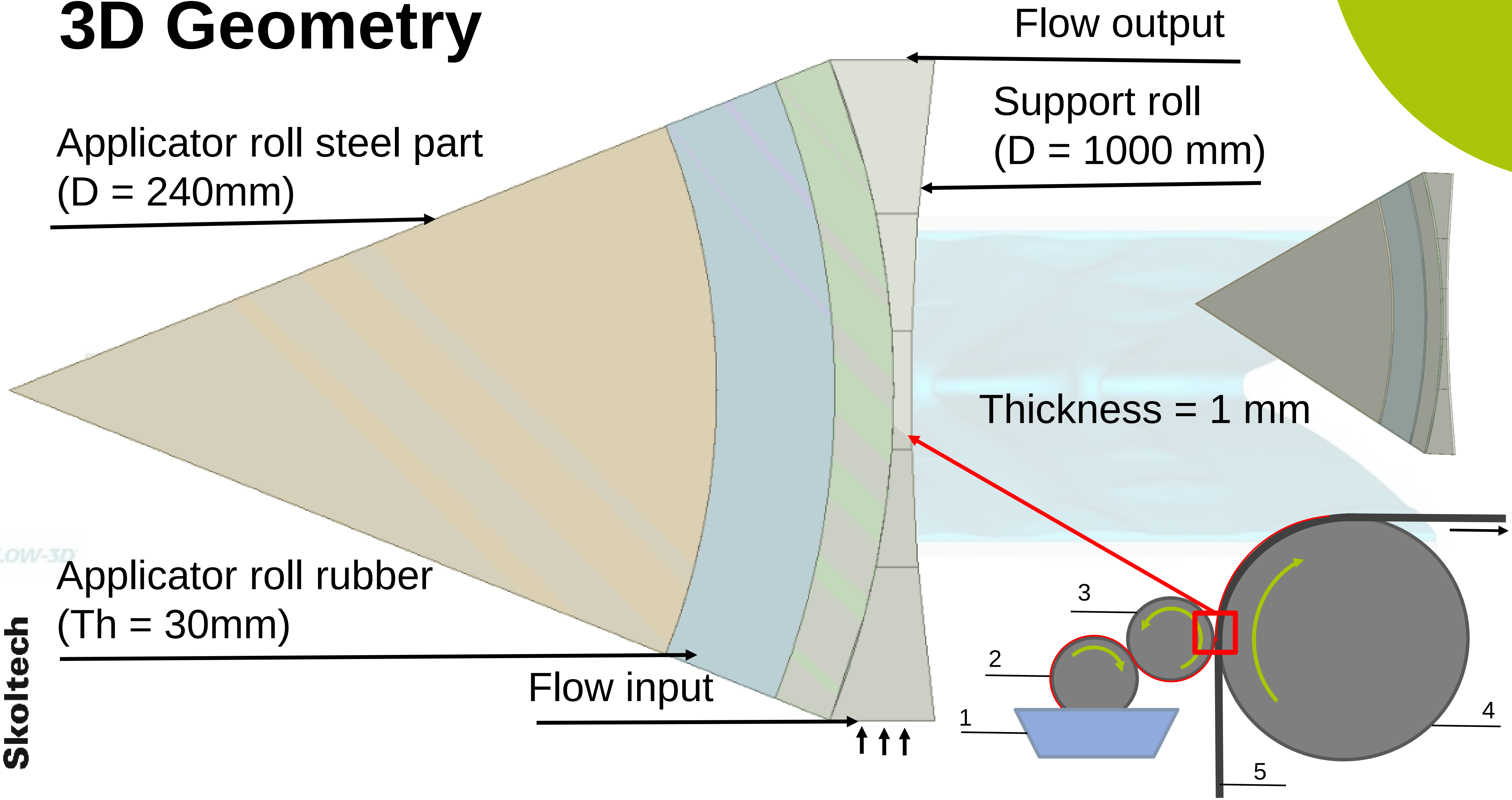
Different face sizing set to
9 geometry segments

104487 nodes
102373 elements

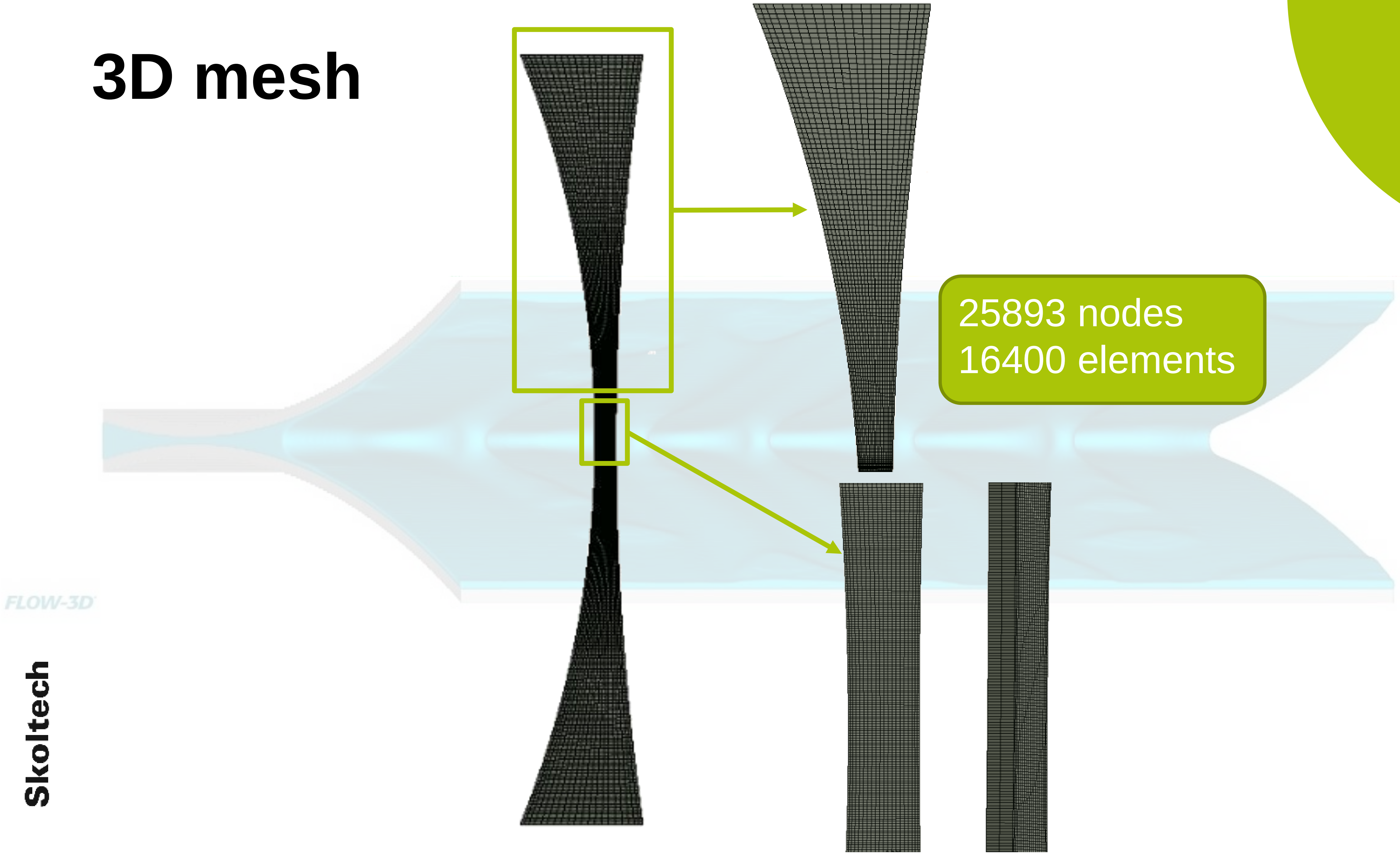




3D Geometry


Flow output
Support roll
(D = 1000 mm)
Applicator roll steel part
(D = 240mm)
Thickness = 1 mm
FLOW-3D
Applicator roll rubber
(Th = 30mm)
Flow input
3
2
1
4
5

3D mesh



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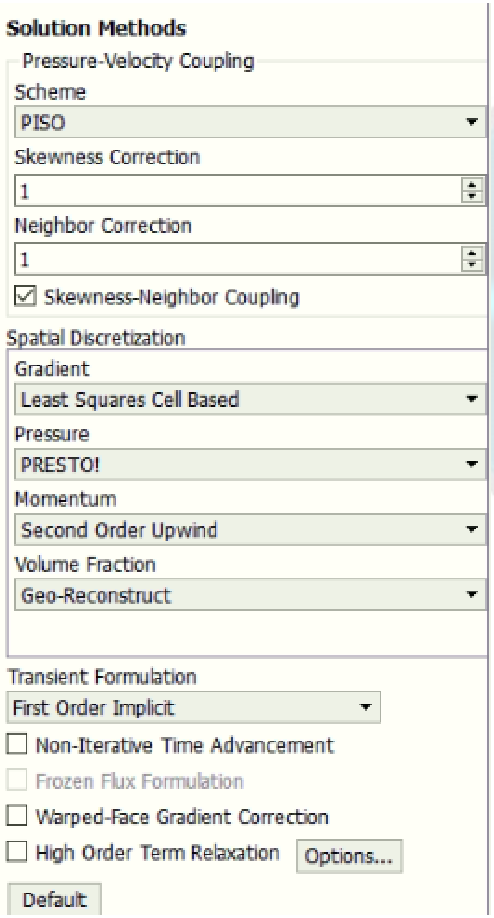
Models setup

Multiphase model: VOF (Volume of Fluid) with Explicit formulation with 2 phases (paint - primary phase and air - secondary phase)



Mainly solutions methods were chosen based on the *Best Practices for Modeling Thin Liquid Film Coating Flows in FLUENT* official Ansys document

Method that gives you the clearest and cleanest interface is the explicit with geo-reconstruct.

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Governing equations

VOF continuity equation for secondary-phase:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right)+\nabla\cdot\left(\alpha_q \rho_q \vec{v}_q\right)=S_{\alpha_q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right]$$

Primary-phase volume fraction

$$\sum_{q=1}^{n}\alpha_q=1$$

Momentum equation:

(For the whole domain, depends on volume fraction through μ and ρ)

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\,\vec{v})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right]+\rho\vec{g}+\vec{F}$$

Continuity equation solved in **explicit formulation** via the following equation:

$$\frac{\alpha_q^{n+1}\rho_q^{n+1}-\alpha_q^{n}\rho_q^{n}}{\Delta t}V+\sum_f\left(\rho_q U_f^n \alpha_{q,f}^n\right)=\left[\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)+S_{\alpha_q}\right]V$$

Nomenclature:
p – primary-phase
q – secondary-phase
S – source term = 0
n – index for the previous term
n + 1 – index fro the new (current) time step
$\alpha_{q,f}$ – face value of the *q* volume fraction, computed from second-order upwind scheme
V – volume of the cell
U_f – volume flux through the face based on normal velocity

Rheology equations and setup

Power Law studied with temperature dependence Arrhenius law

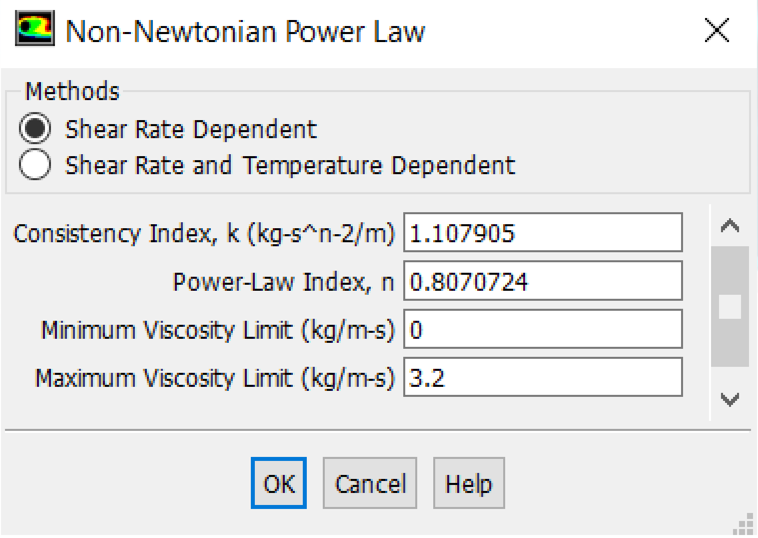
$$\eta = k\dot{\gamma}^{n-1} H(T)$$

$$H(T) = exp\left[\alpha\left(\frac{1}{T - T_0} - \frac{1}{T_\alpha - T_0}\right)\right]$$

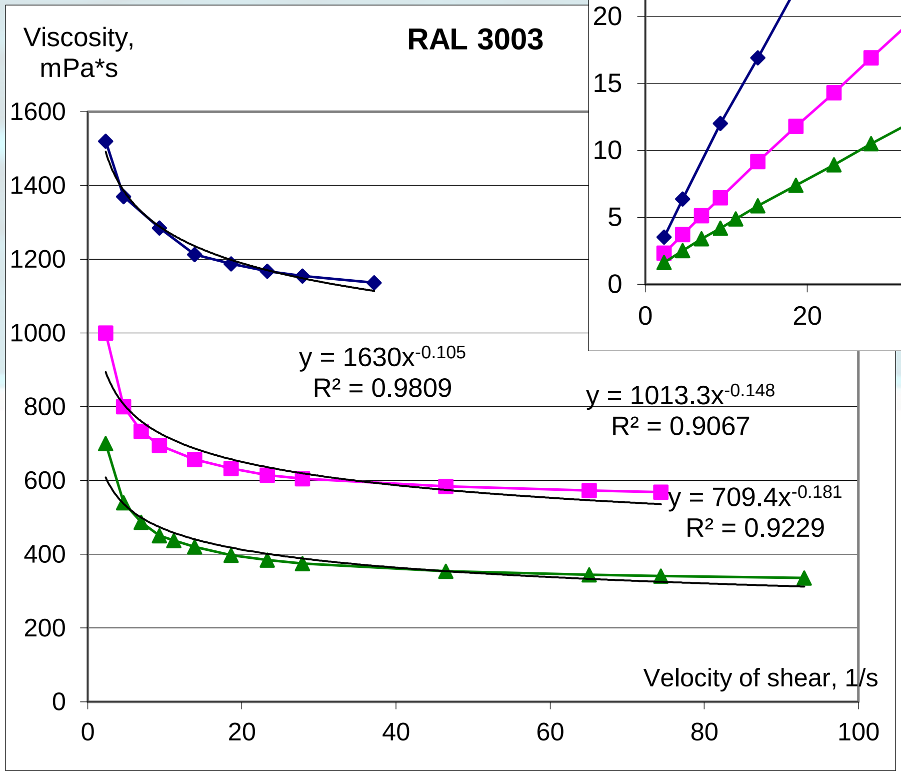
η - Dynamic viscosity
$\dot{\gamma}$ - Shear rate

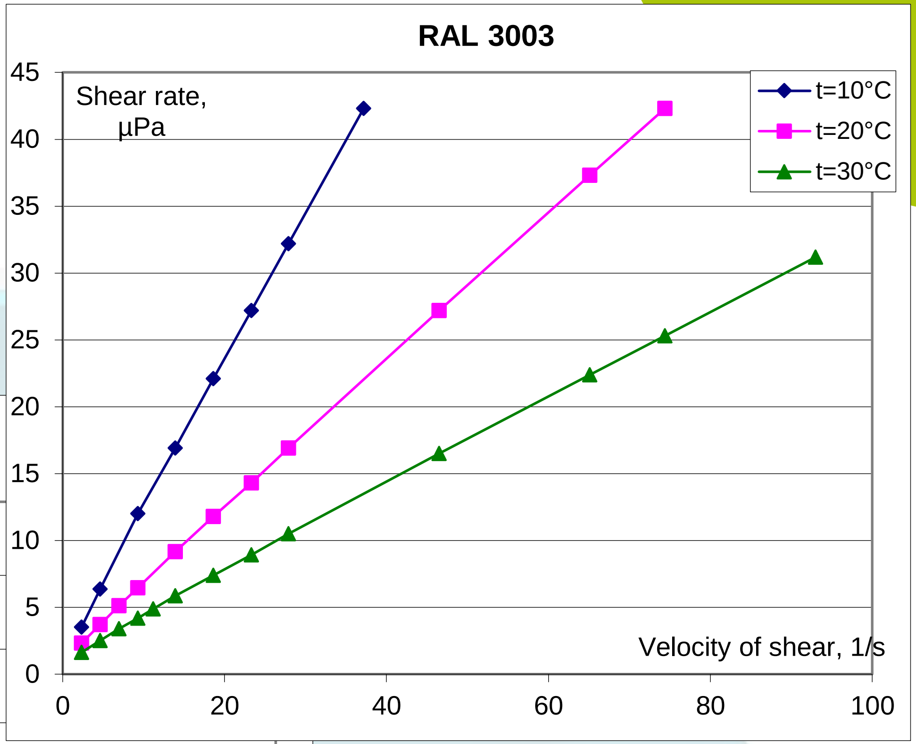
T_α - Reference temperature (where $H(T)$ = 0)

Settings Used:



Density - 1280 kg/m3

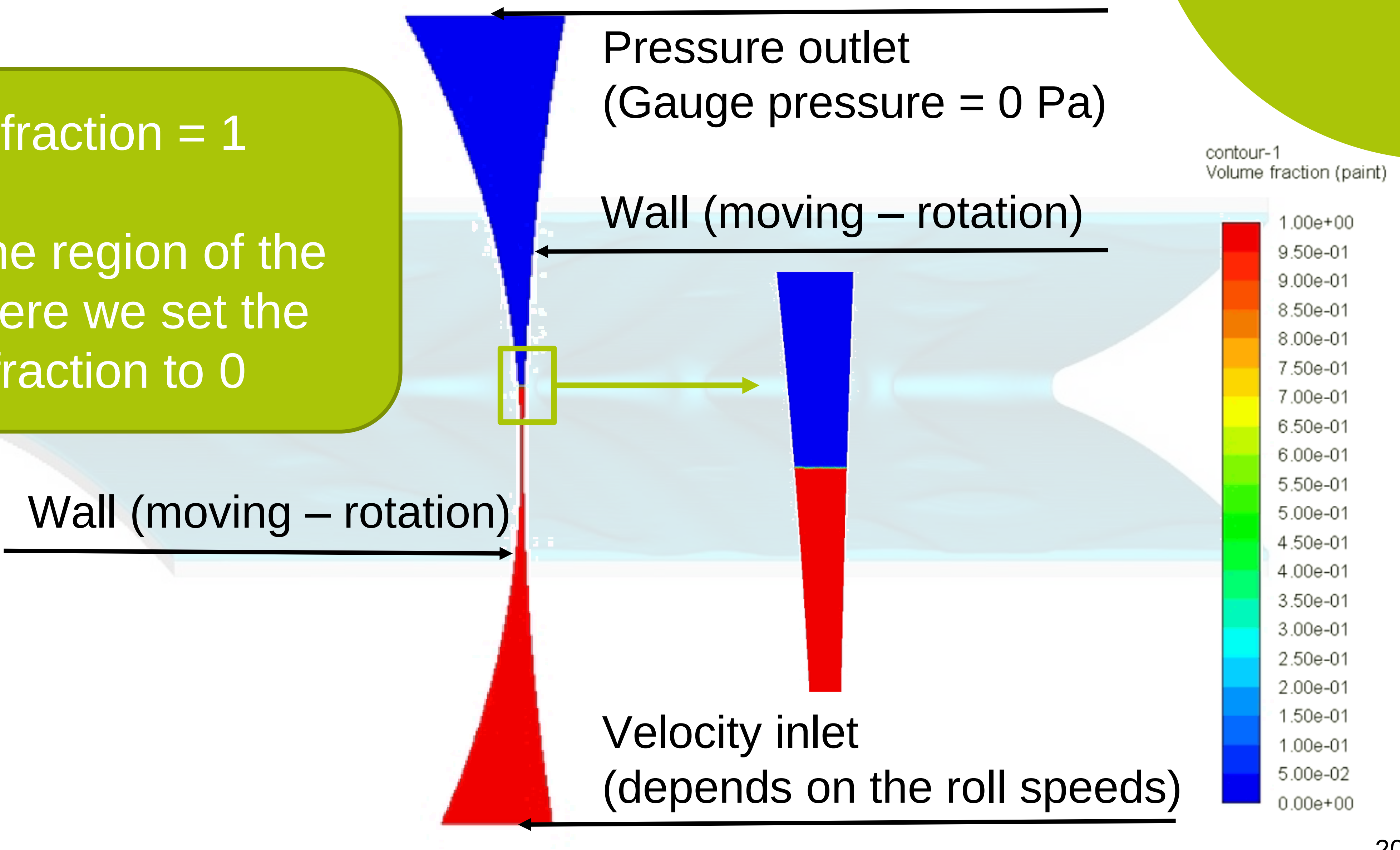




Boundary and Initial conditions

Air Volume fraction = 1

But patch the region of the domain, where we set the air volume fraction to 0



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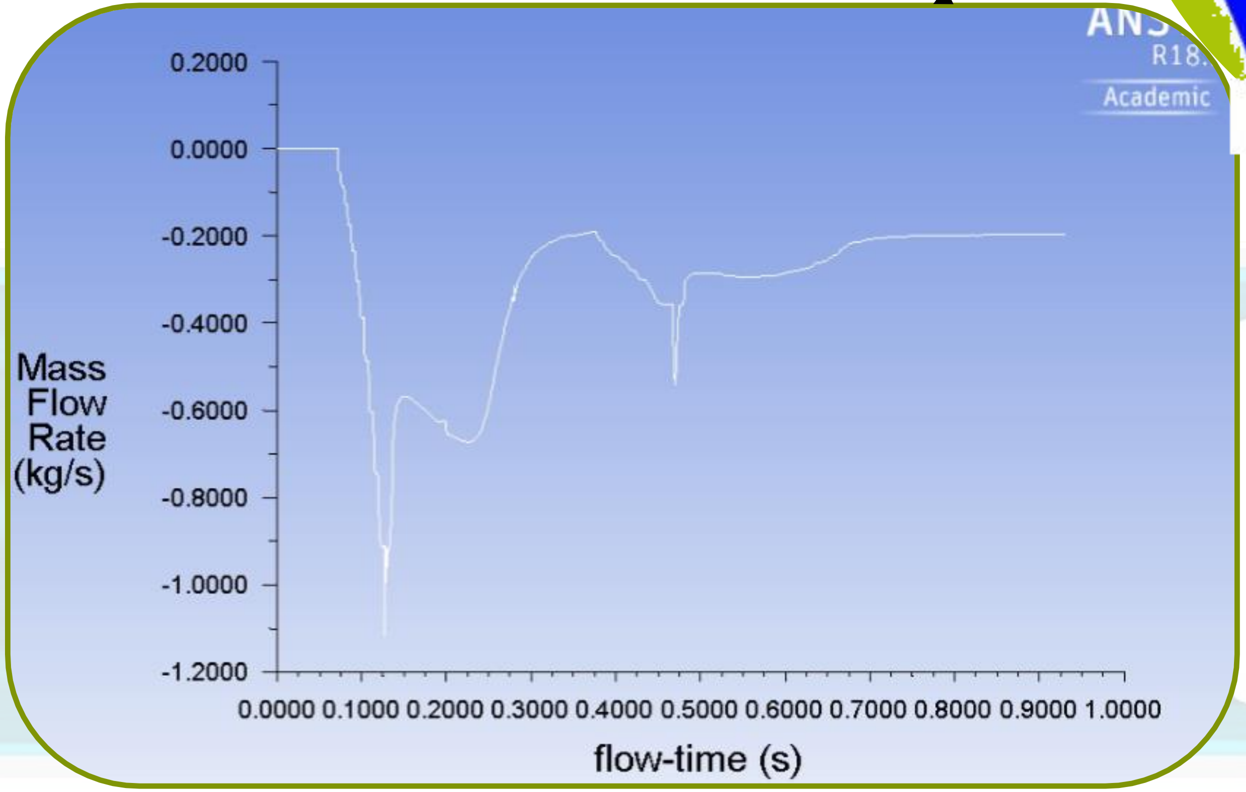
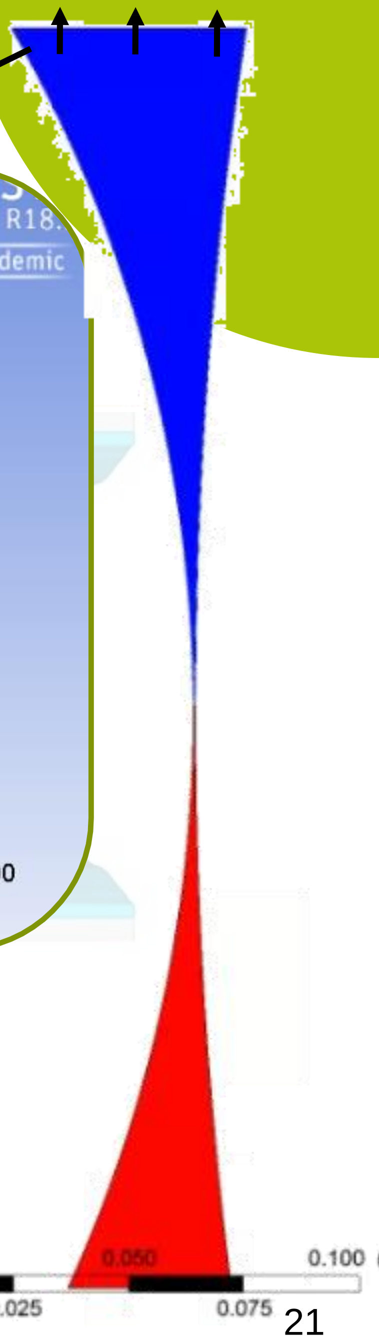
Results: Paint thickness analysis

Settings:

- Distance between rolls – 4e-4 m
- Applicator roll – 1 rad/s
- Support roll – 1.4-2 rad/s
- Density - 1280 kg/m3
- Viscosity – 1.2 kg/m*s
- Inflow - ~0.3 m/s per each support roll speed rad/s
- Time step – 3e-5 s
- Steps ~ 30000



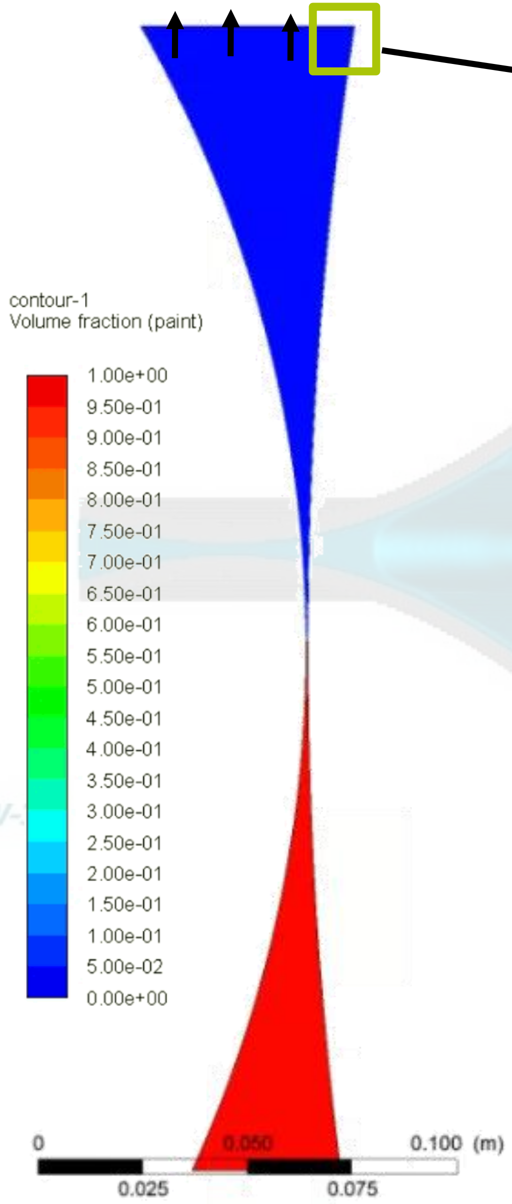


The calculation is done, when we observe the stability of coating thickness on the rolls

=

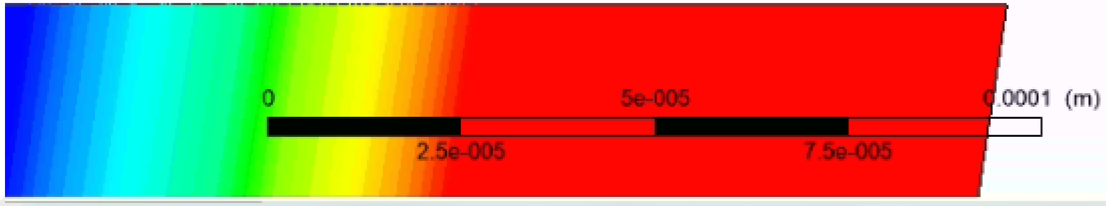
Constant mass flow rate at the output

Results: Paint thickness analysis

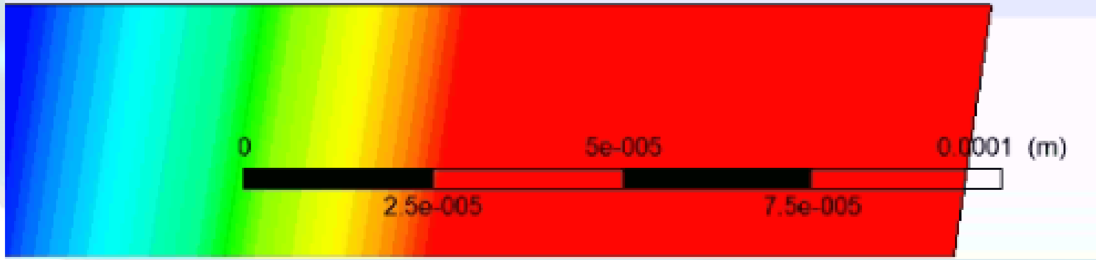


Measurement of the support roll output area

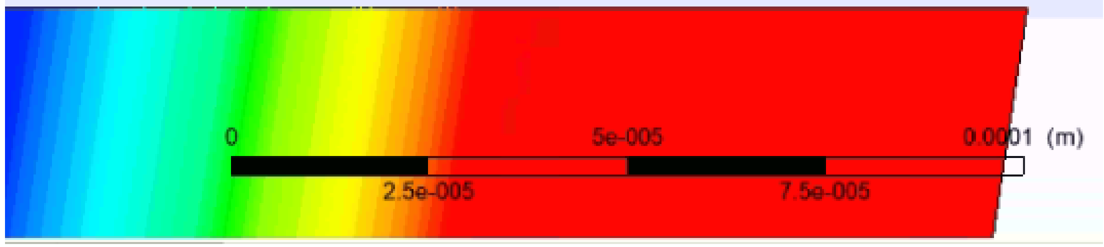
Support roll speed



1.4 rad/s



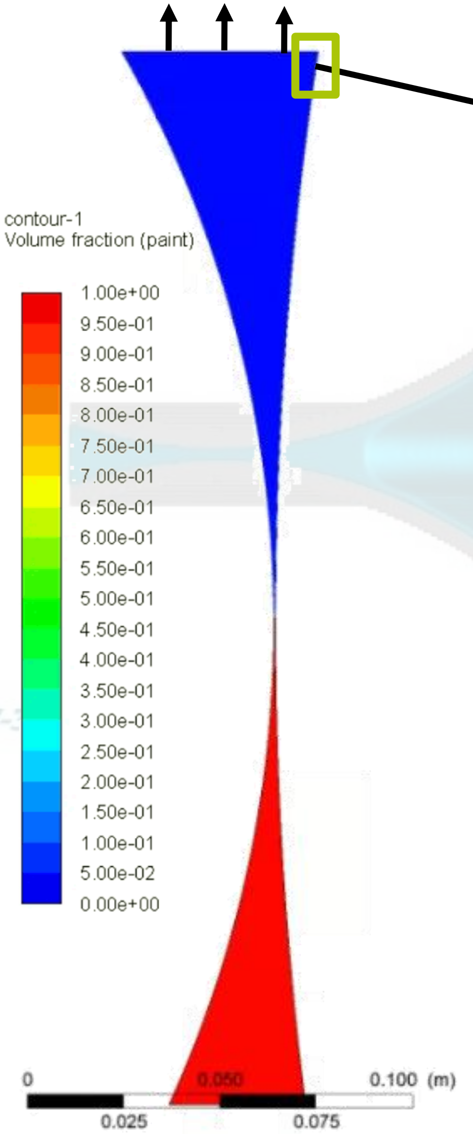
1.5 rad/s

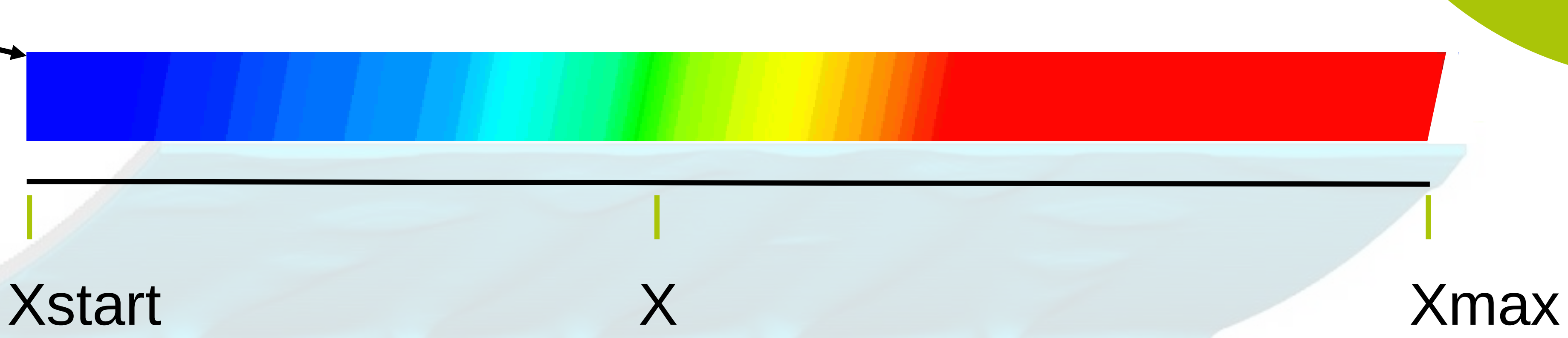


1.6 rad/s

Applicator roll speed is constant = 1 rad/s

Results: Thickness measurement automation





1. Select the 1D X direction region
2. Divide the region into N parts
3. Iteratively then at every n step the paint volume fraction
4. Where paint volume fraction > 0.5 – X
5. Paint thickness = Xmax-X

Implemented via Ansys workbench script using Python language

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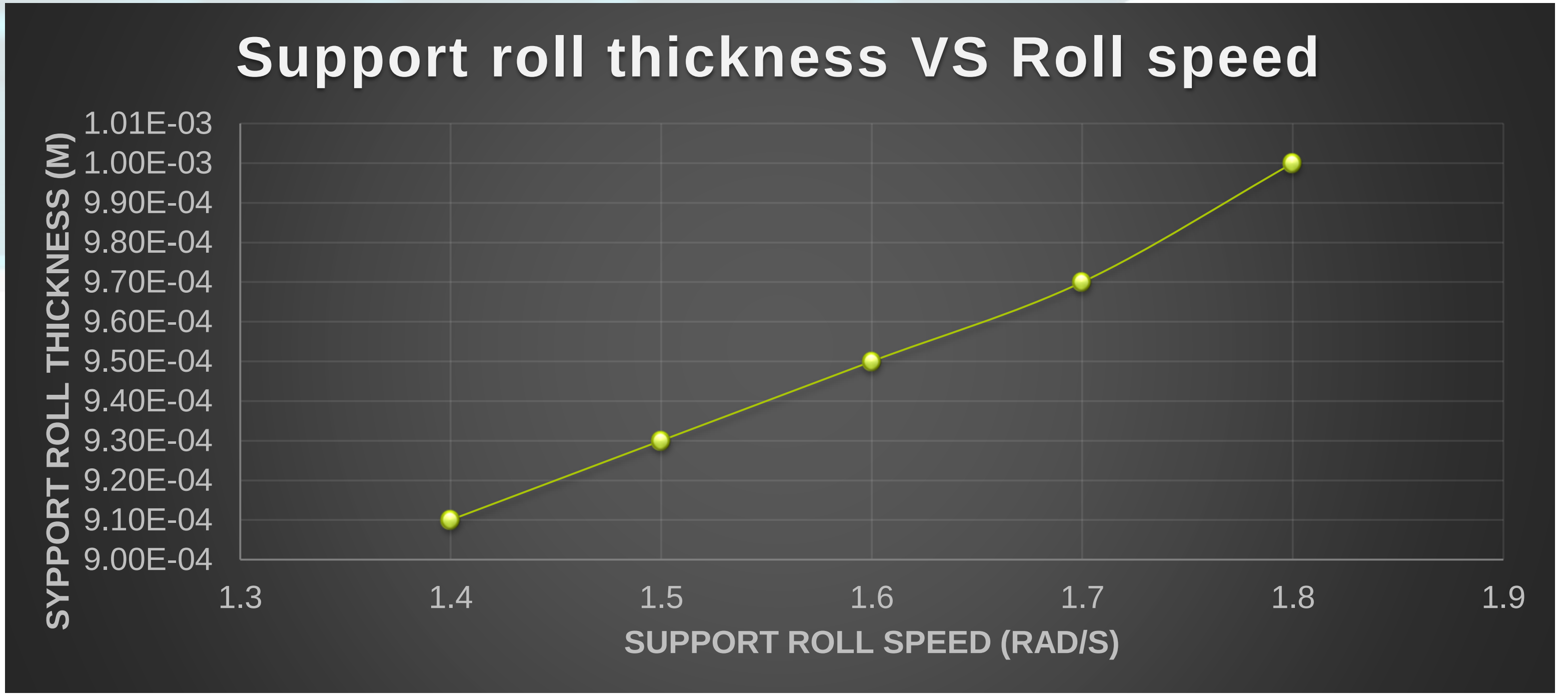
Results: Paint thickness analysis

Support roll (rad/s)	Applicator roll thickness (m)	Support roll thickness (m)	Time steps	Mass flow output (kg/s)	Mass flow input (kg/s)
1.4	5.7e-005	**9.10E-04**	26000	-0.187039	0.182261
1.5	4.7e-005	**9.30E-04**	31004	-0.197878	0.195931
1.6	4.5e-005	**9.50E-04**	33435	-0.211327	0.2096
1.7	4.5e-005	**9.70E-04**	28420	-0.229579	0.227826
1.8	4.6e-005	**1.00E-03**	30501	-0.245842	0.243774



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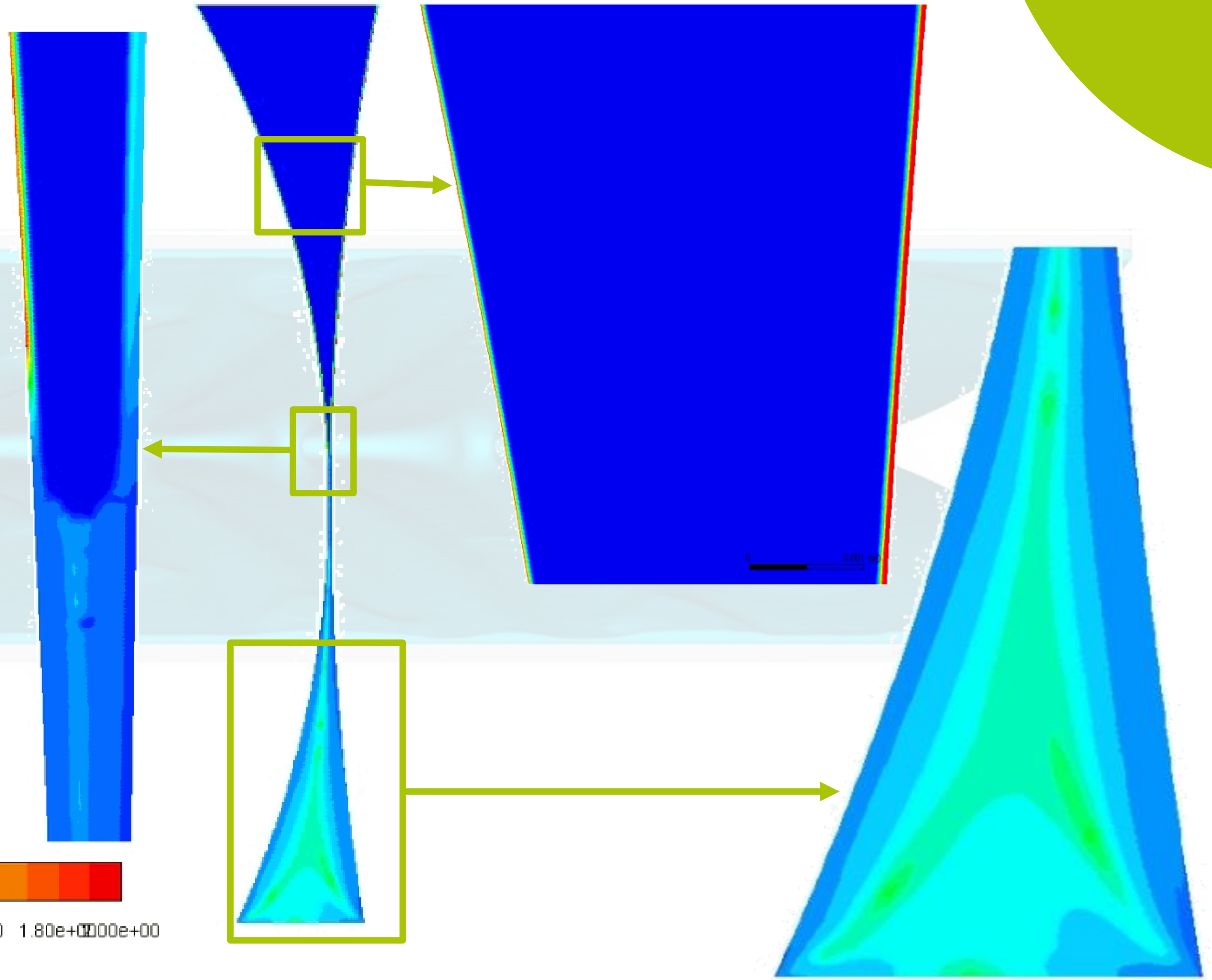
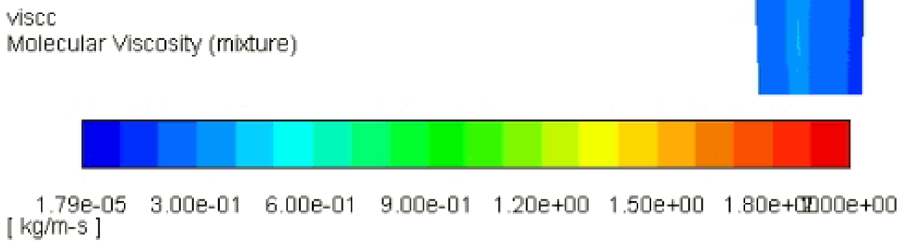
Results: Rheology Research

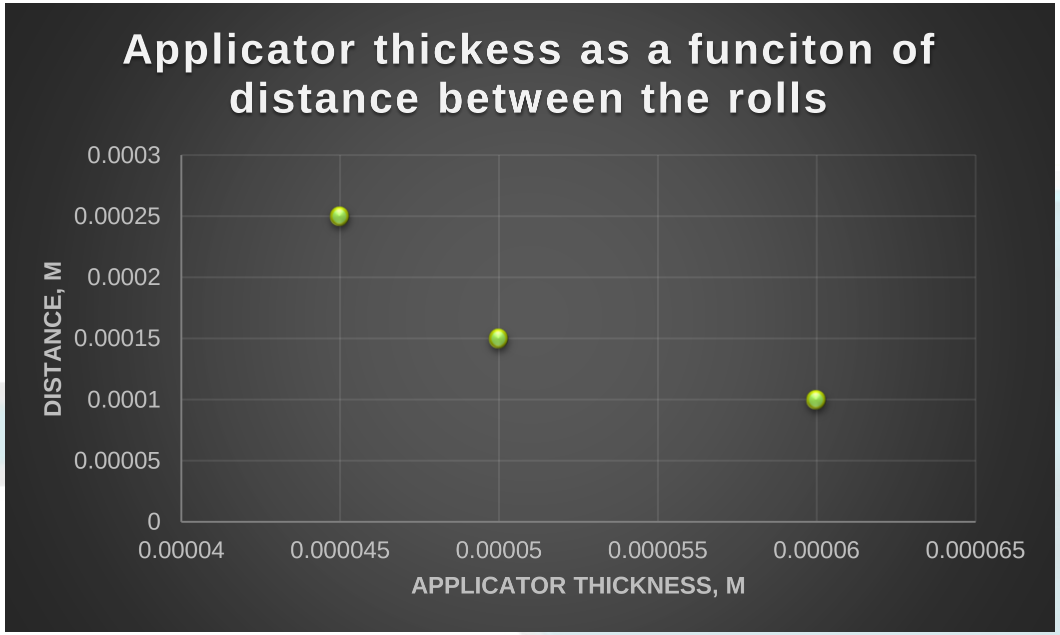
Notes:

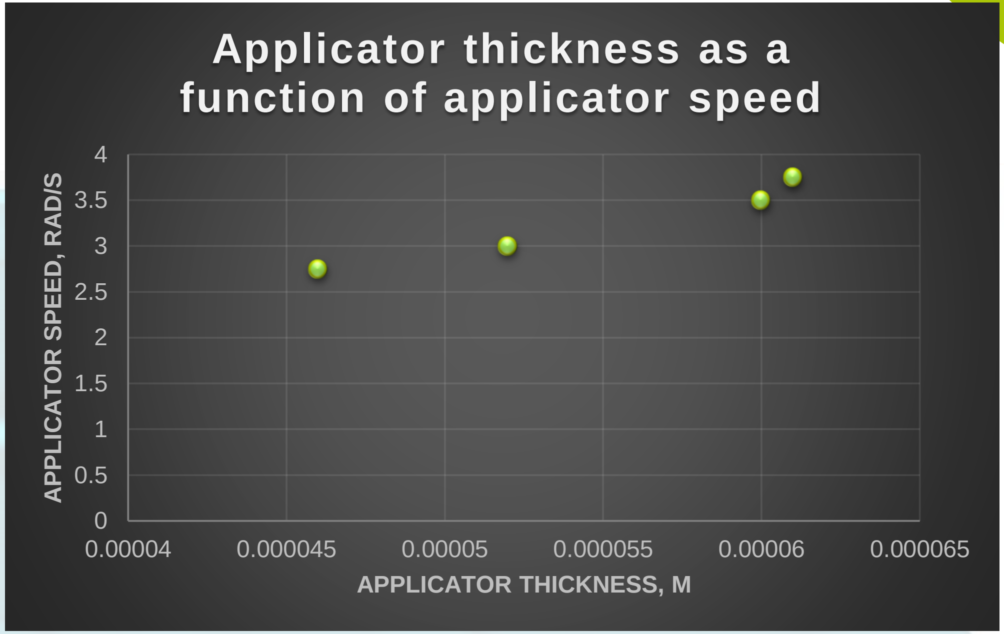
- More viscous liquid neat the walls towards the outlet
- The least viscous liquid is near meniscus





Results: Rheology thickness analysis





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Support roll thickness speed was constant (7.5E-04 m)→
Support roll thickness did not depend on distance or applicator speed variations!

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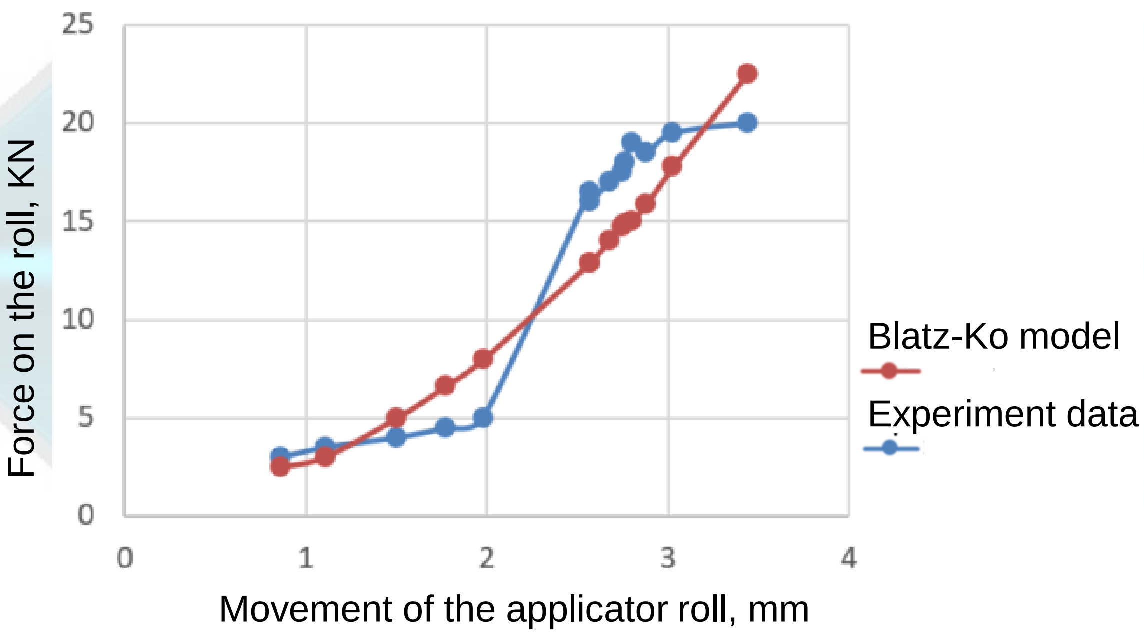
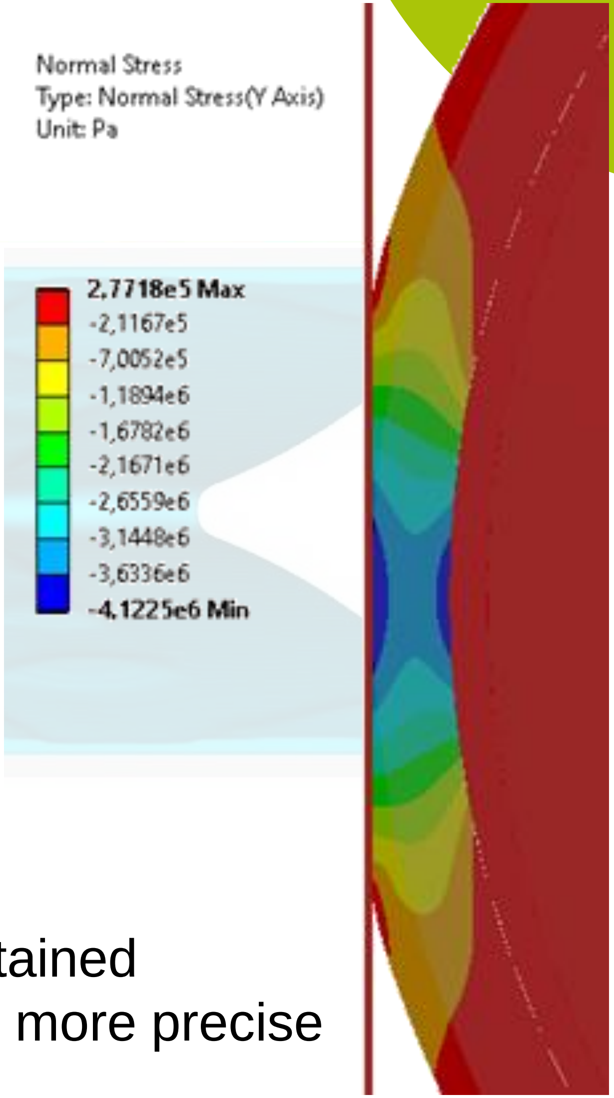
Results: Elasmoter model optimization

Elastomer models research and analysis based on the preliminary data
Elastomer model parameters optimization with pSeven

Elastomer models studied:
- Mooney-Rivlin
- Blatz-Ko

Deformation diagrams





- Blatz-Ko model was chosen and preliminary model parameters obtained
- More experiments on elastomers were performed, we can develop more precise

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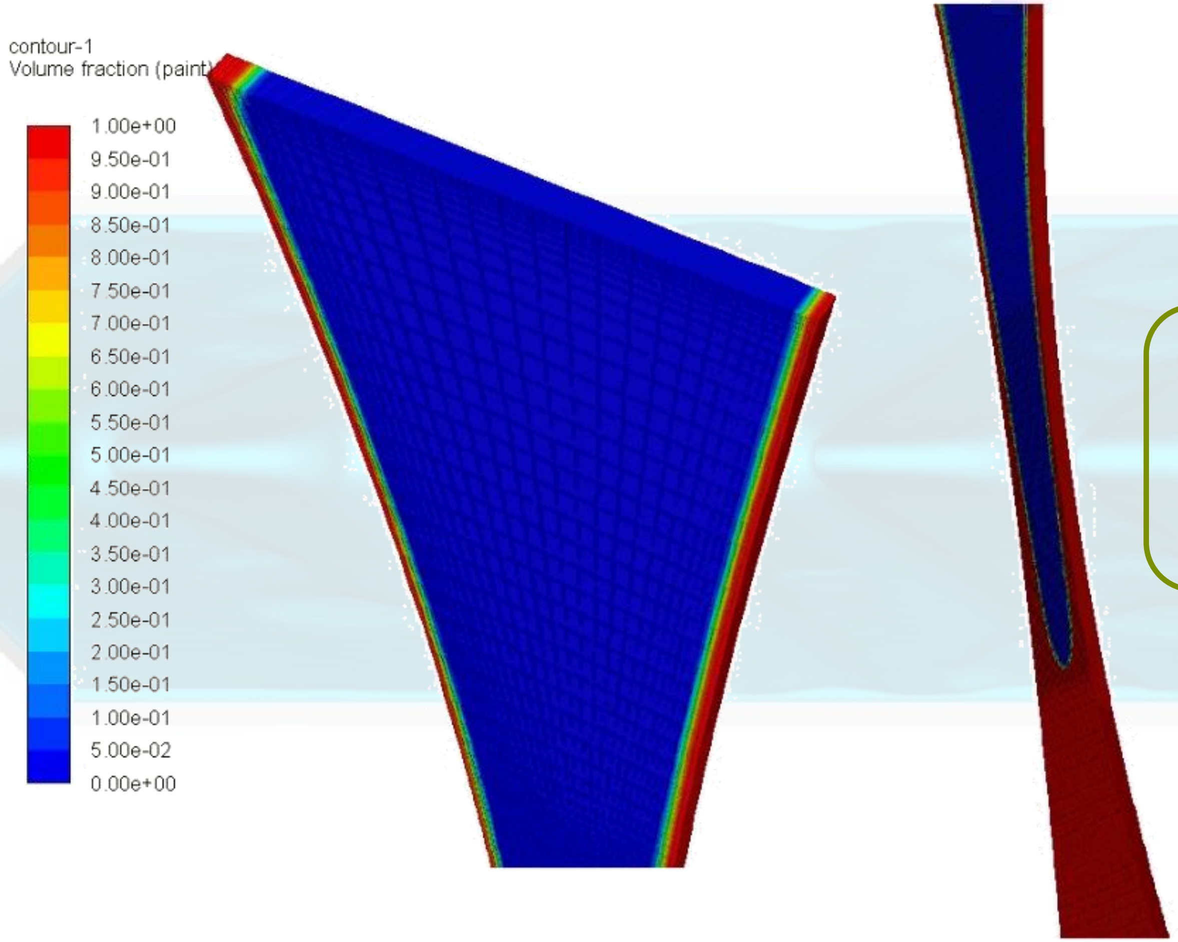
Results: 3D fluid model simple result

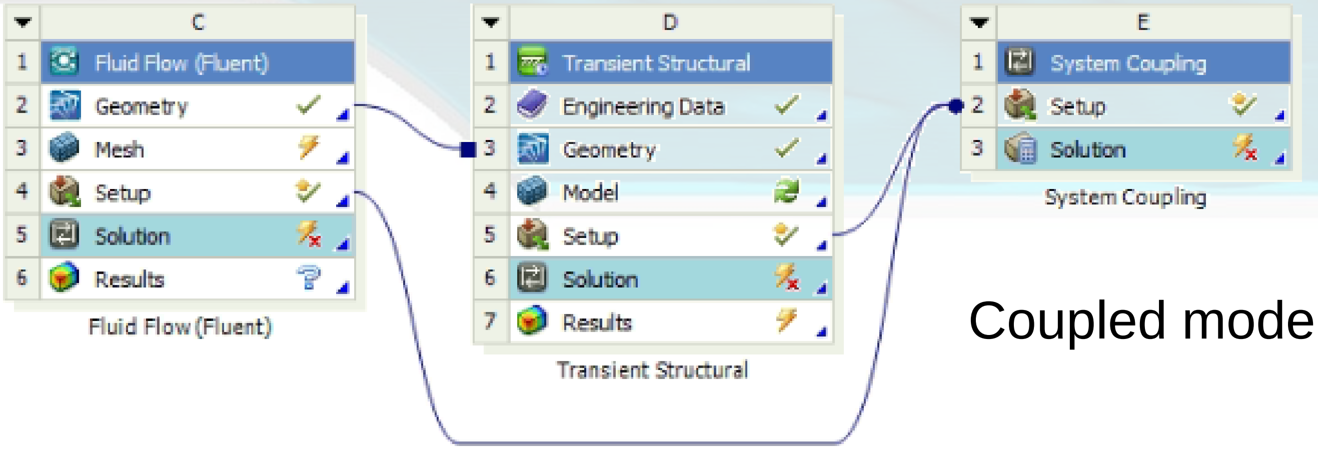
Fluid 3D model ready to be used in the coupled model computations



0.004 m thickness on the support roll

Future plans

1. Obtain coupled model results and validate it
2. Improve the model with more experimental data
3. Get results for various operating parameters → create dataset
4. Recommendation system development



Coupled model setup

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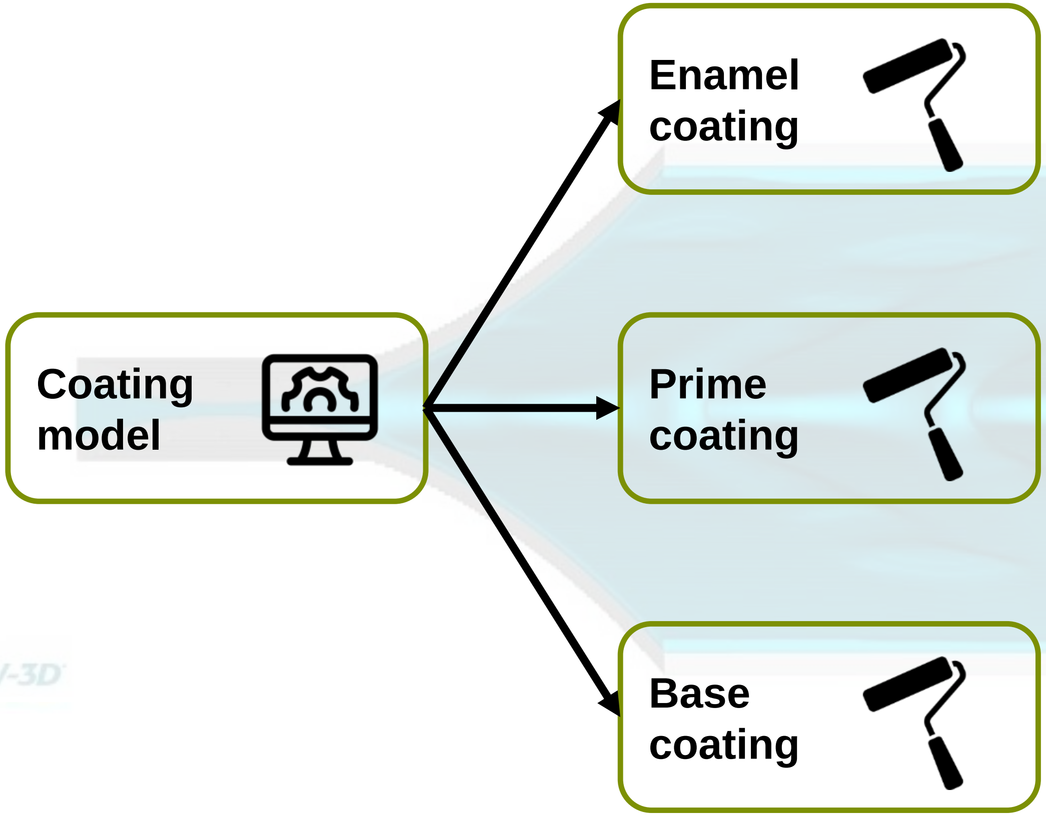
Recommendation system features



1. Fine tuning of the system
2. Best parameters optimization for required system
3. Deformation roll wear control
4. Real time process control and adjustments as needed

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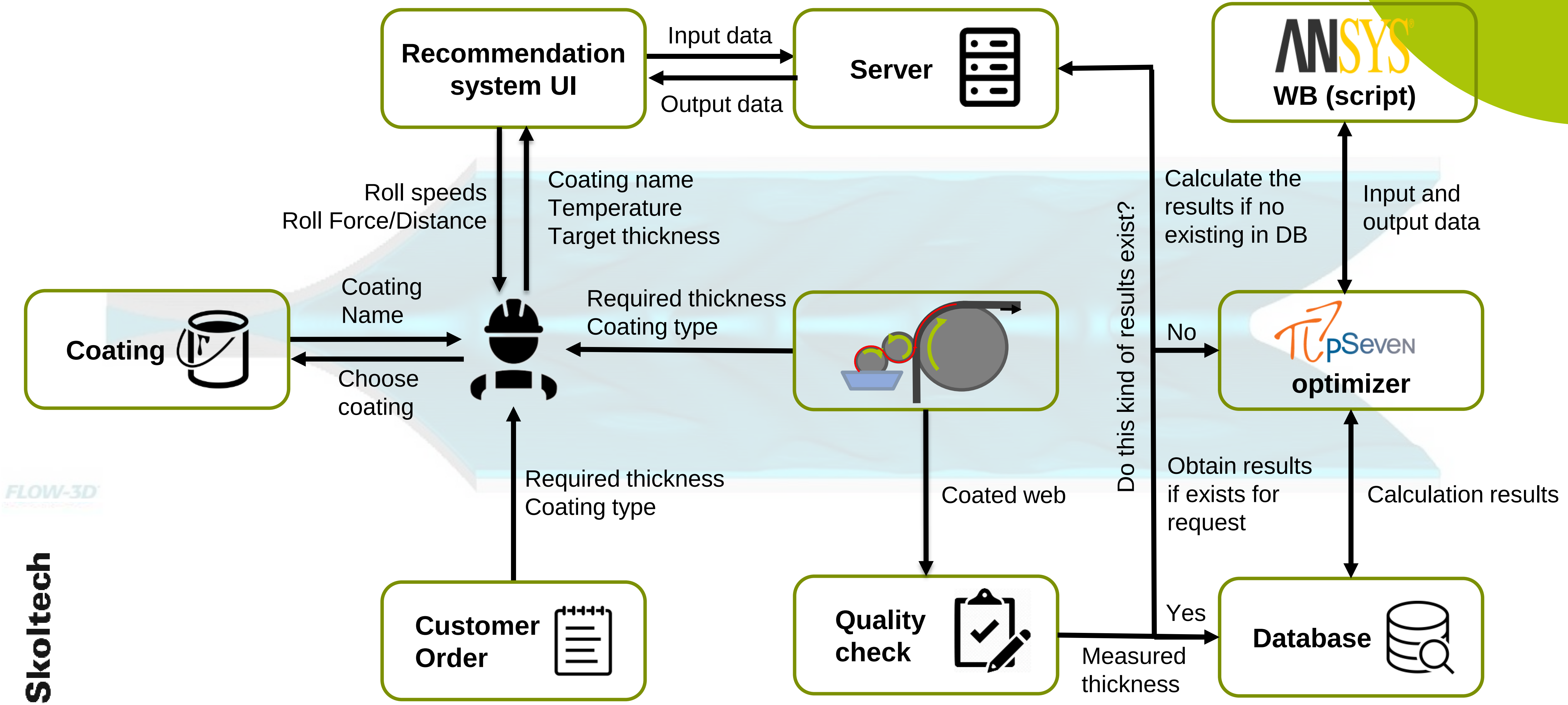
Recommendation system architecture



Conclusions

- Researched deeply the topic and the system
- Learned how to work with the CFD and multiphase
- Managed to implement non-Newtonian model
- Proved that we our model can provide stable and consistent results
- Paint thickness mostly depends on the support roll speed
- **Build the foundation for the recommendation system**

FLOW-3D

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Acknowledgements

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  For performing the elastomer model optimization

Thx.

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