Steps for the Optimization of Pipe and Tubing Extrusion Dies

By

John Puentes
Tim A. Osswald

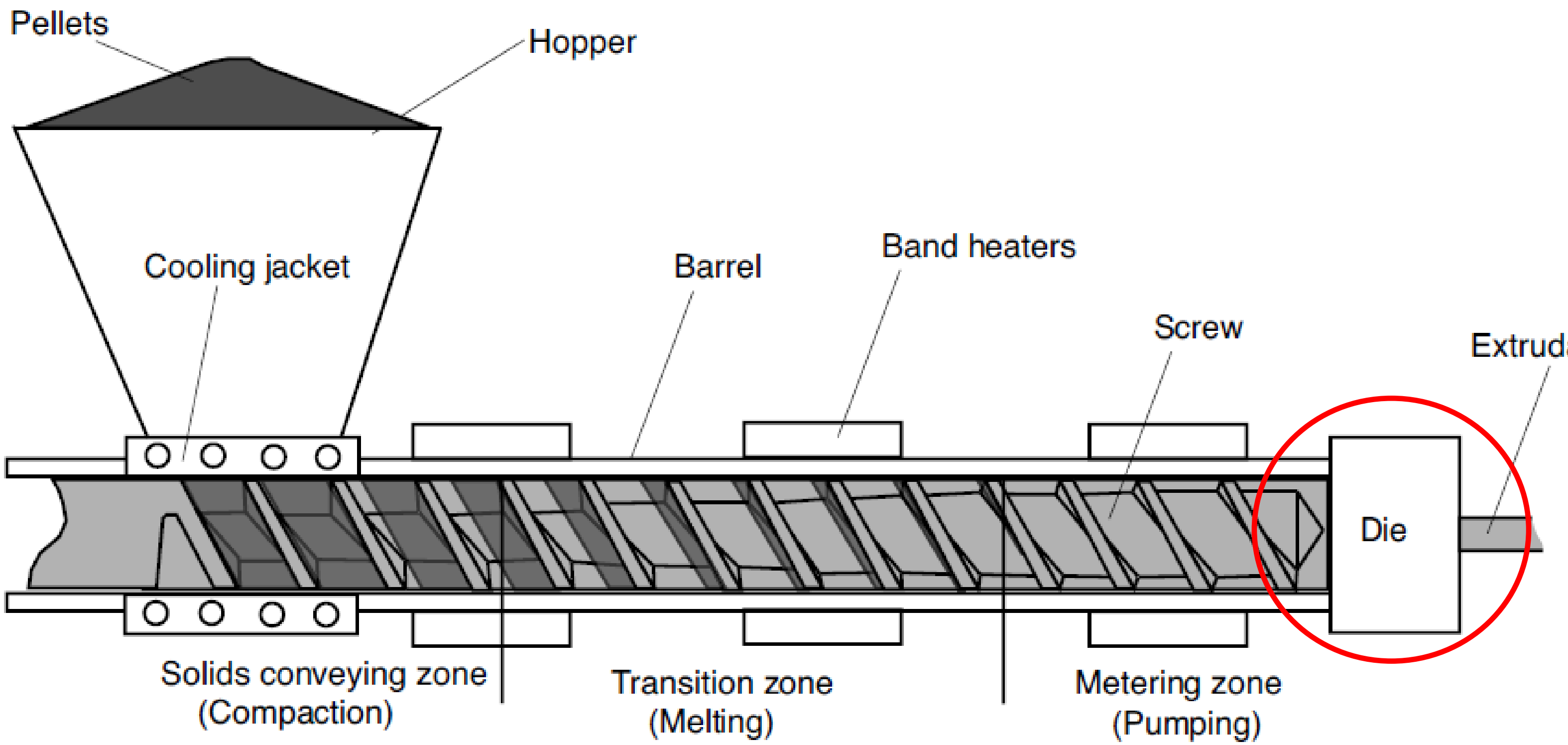
UNIVERSITY OF WISCONSIN-MADISON COLLEGE OF ENGINEERING
Polymer Engineering Center

Steve Schick
Jed Berg

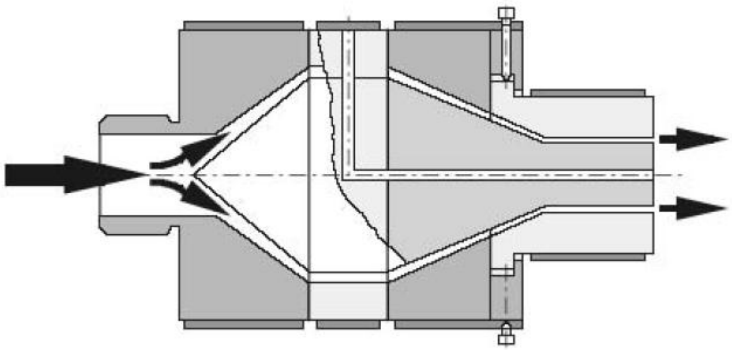
Teel PLASTICS, INC.

Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston

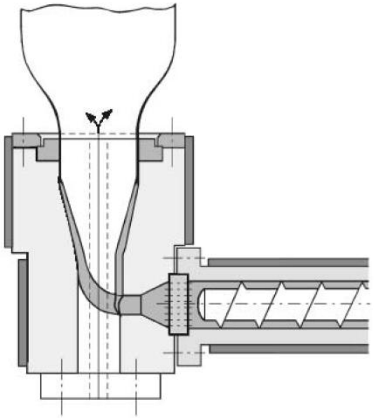
Extrusion of HDPE pipes



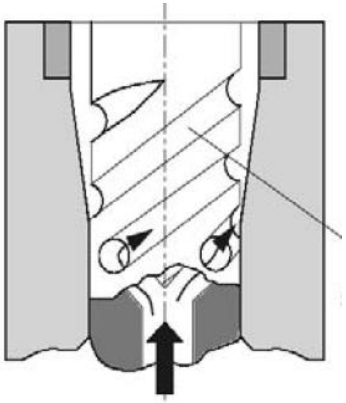
Pipe and Tubular Dies



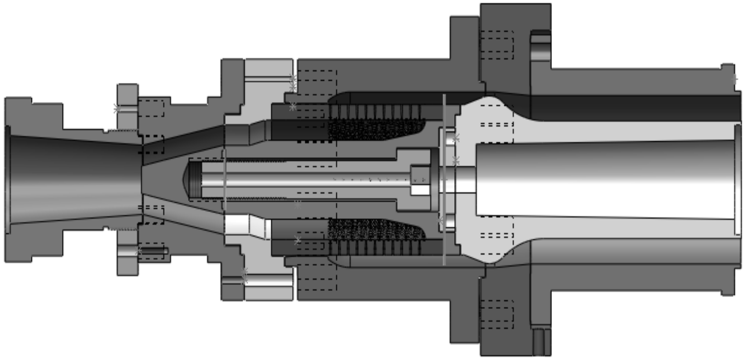
Spider leg tubing die



Cross-head tubing die

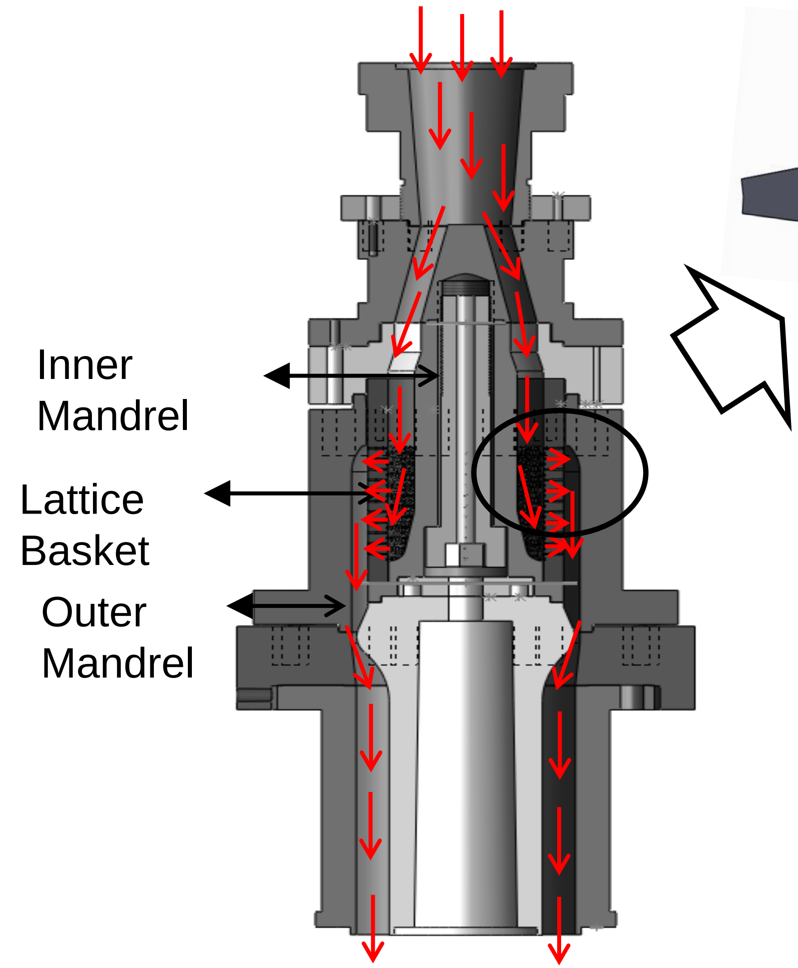


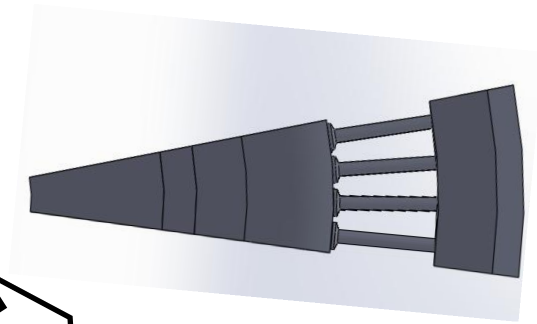
Spiral mandrel

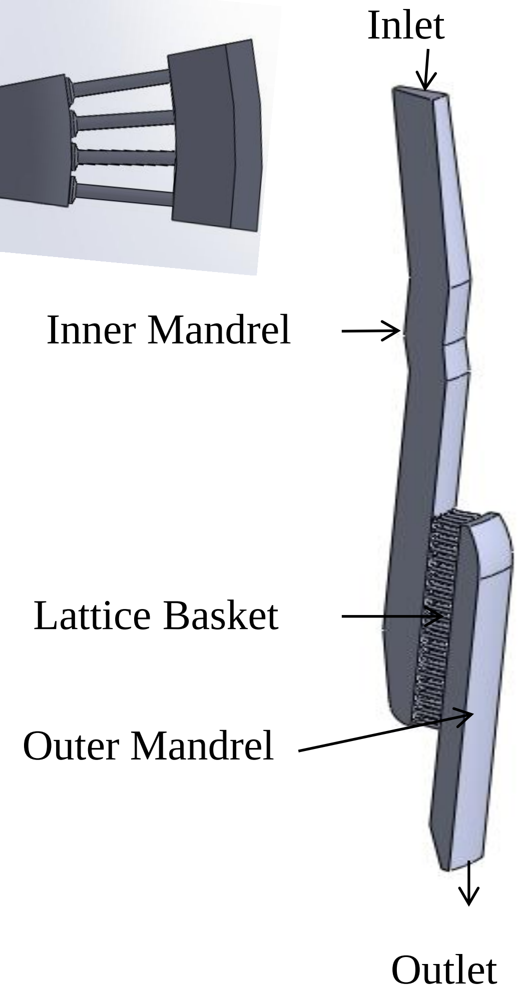


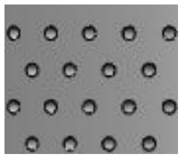
Lattice Basket

Lattice Basket Die









Borehole pattern

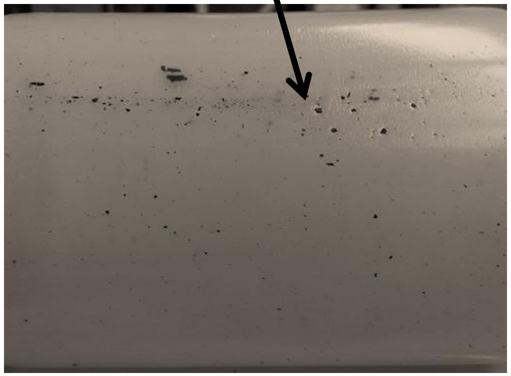
Degradation in HDPE

Chemical reaction

* Temperature history
* Shear history
* Longer Residence time

* Oxygen
* Catalyst residuals

Gelation
(small
blemishes)



Detection of degradation in HDPE

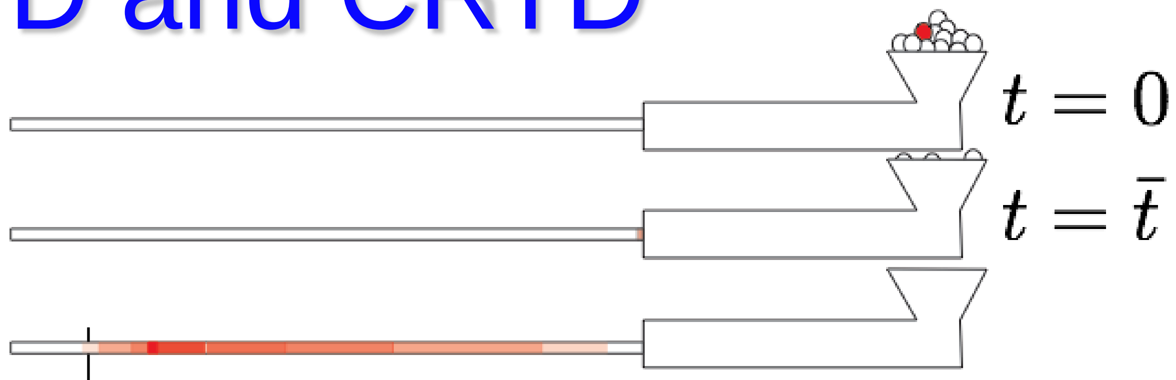
Phillips HDPE (Cross-linking)

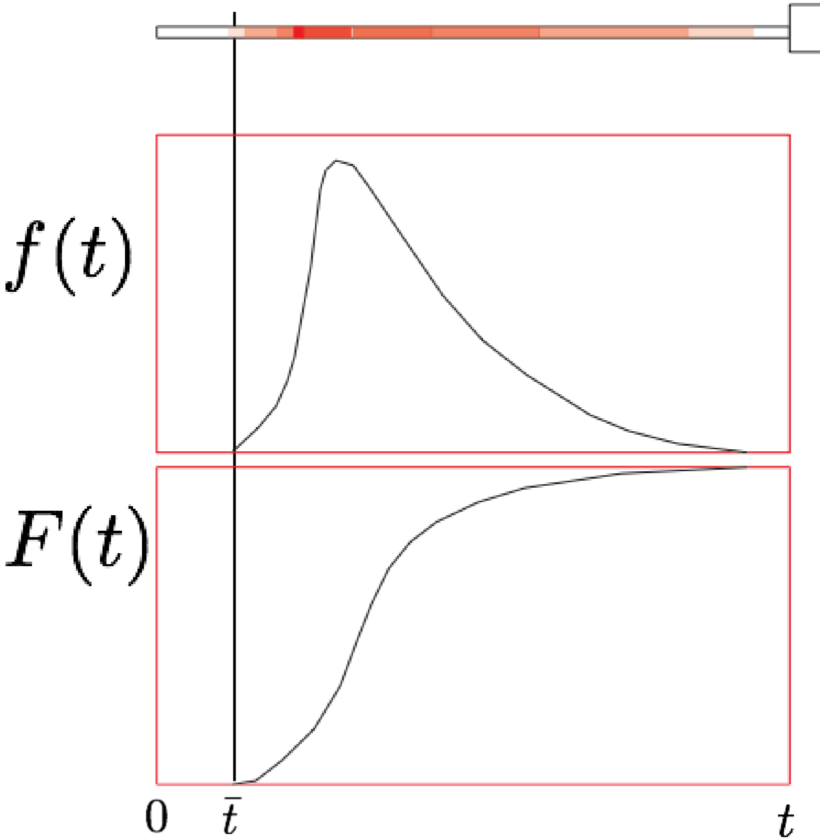
MW ↑

η ↑

MFI ↓

RTD and CRTD





Residence Time Distribution (RTD)

Cumulative Residence Time Distribution (CRTD)

$$F(t) = \int_0^t f(t)dt$$

Processing conditions

Material: *Chevron Phillips Marlex HHM 5202 HDPE*

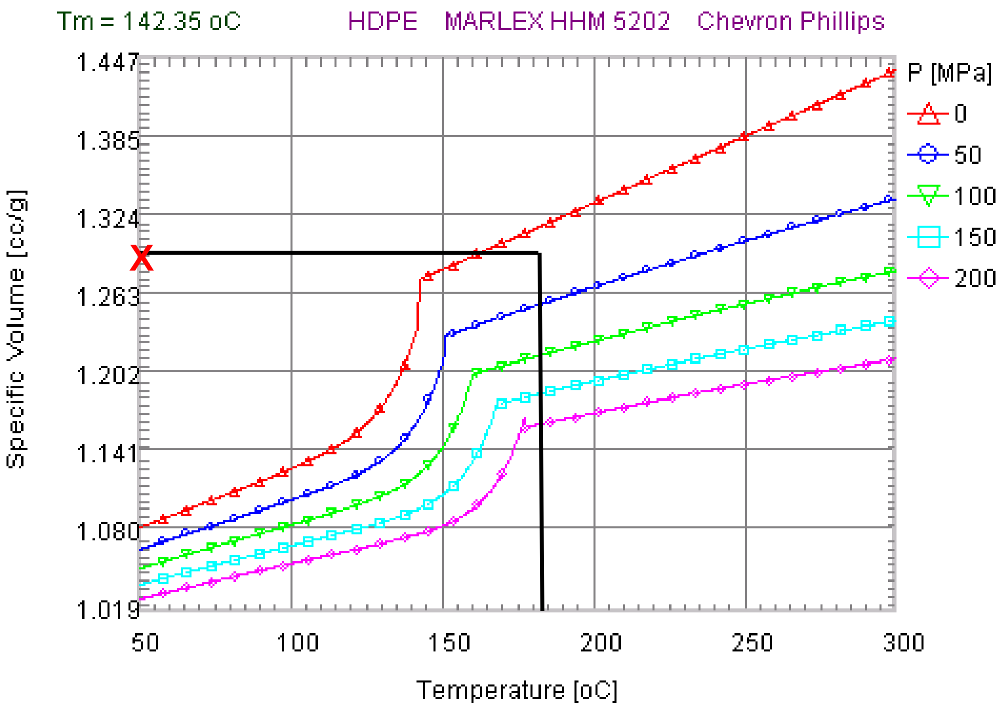
Property	Symbol	English S		SI	
Mass Flow Rate:	$\dot{m}$	450	***lb./h***	0.0567	***m/s***
Diameter of the extruder:	***D***	3.5	***in***	0.0889	***m***
Temperature of the extrudate:	***T***	362	***F***	183.3	***°C***
Melt pressure:	***P***	1925	***Psi***	13.72	***Mpa***
Time to reach steady state:	***t***	2	***h***	7200	***s***

Carreau Model

Shear rate range	$\dot{\gamma}$	10-14000	*s^-1*
power law index	*n*	0.3	*dim.*
time constant		0.0259	*s*
zero shear rate viscosity	η_0	5600	$(N * s)/m^2$
infinite shear rate viscosity	η_∞	0	$(N * s)/m^2$

1. Parameters provided by TEEL Plastics, Inc.

Processing conditions

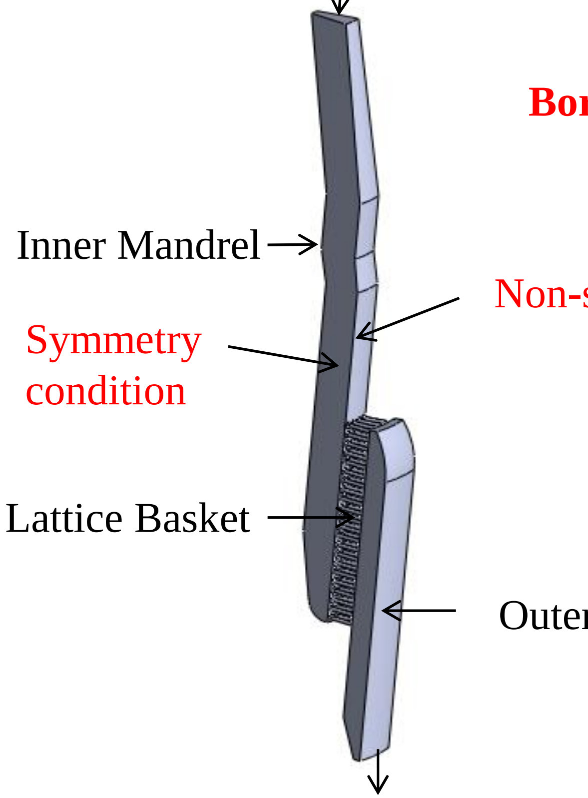


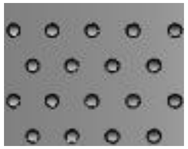
Property	Symbol	English S		SI	
Density (T=183.3 °C): *(By using the PVT diagram)*	ρ	47.837518	lb./ft^3	766.2835	kg/m^3

2 Data obtained from Database MOLDEX 3D Molding Innovation

Lattice Basket simulation

$\dot{m}$



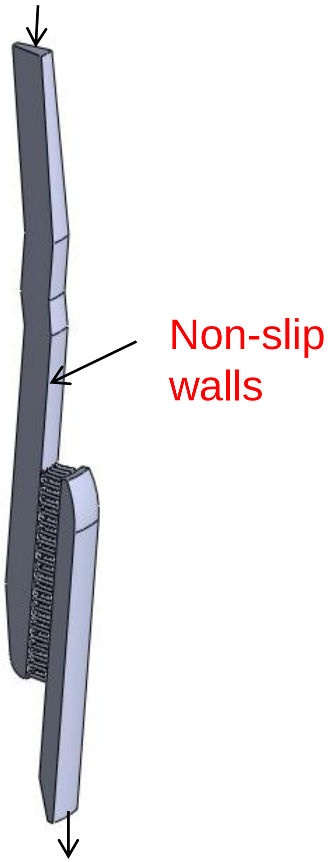


Borehole pattern

ΔP

v, ΔP and streamlines

2000 Particles



Outlet

Particle traces, Poincaré sections, CRTD

Mathematical model

Assumptions

3D model
Steady state
Inertia F. - negligible Re<<1
Body Forces - negligible Ps<<1
Isothermal stage
Bird-Carreau model

$$\nabla \cdot \mathbf{u} = 0 \qquad (1)$$

$$0 = -\nabla p - [\nabla \cdot \boldsymbol{\tau}] \qquad (2)$$

$$\boldsymbol{\tau} = \eta \dot{\boldsymbol{\gamma}} \qquad (3)$$

$$\dot{\boldsymbol{\gamma}} = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^t) \qquad (4)$$

$$\frac{\eta - \eta_o}{\eta - \eta_\infty} = [1 + (\lambda \cdot \dot{\gamma})^2]^{\frac{(n-1)}{2}} \qquad (5)$$

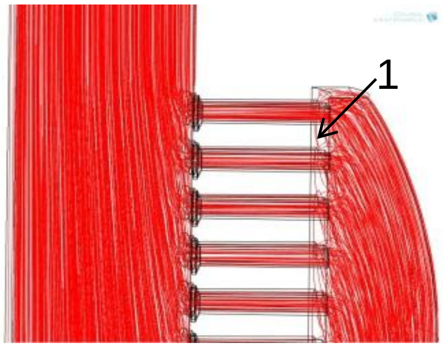
$$\dot{\gamma} = \sqrt{\frac{1}{2}(\dot{\boldsymbol{\gamma}} : \dot{\boldsymbol{\gamma}})} \qquad (6)$$

Boundary Conditions

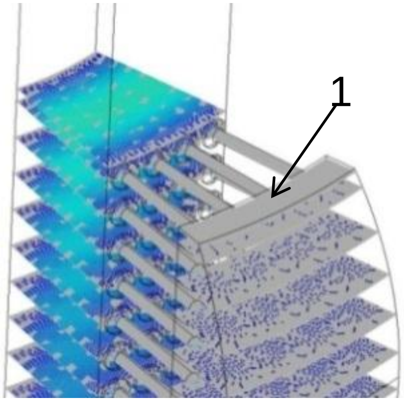
Inlet: Constant mass flow rate
Outlet: Pressure gradient equal to zero
Walls: Non-slip
Cut sides: symmetry condition

Implication of the lattice basket

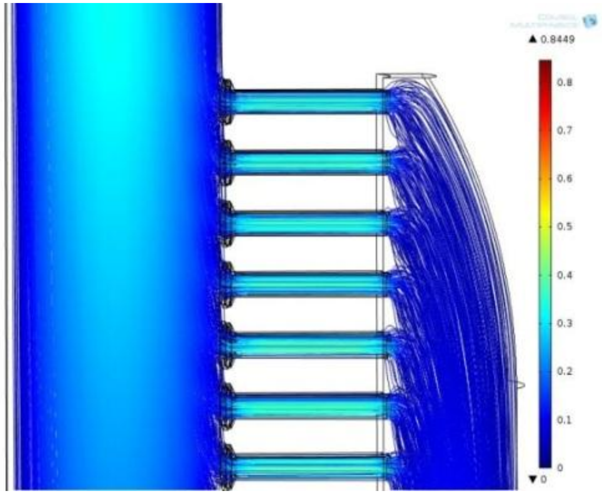
Streamlines



Poincaré sections

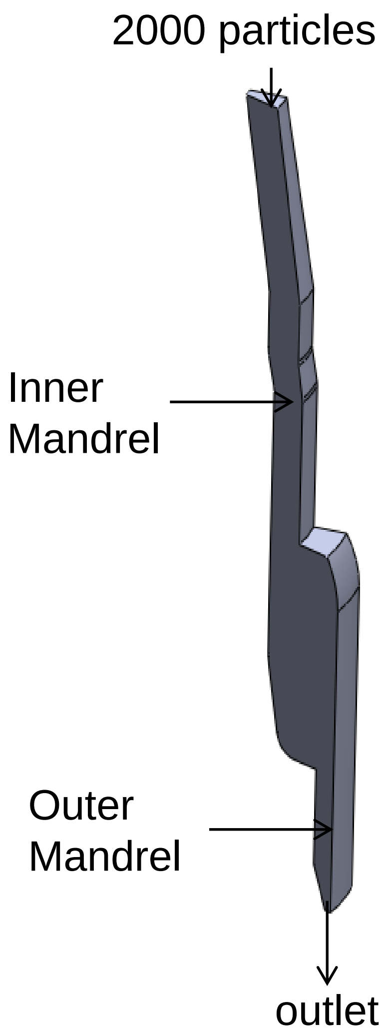


Tracer curves

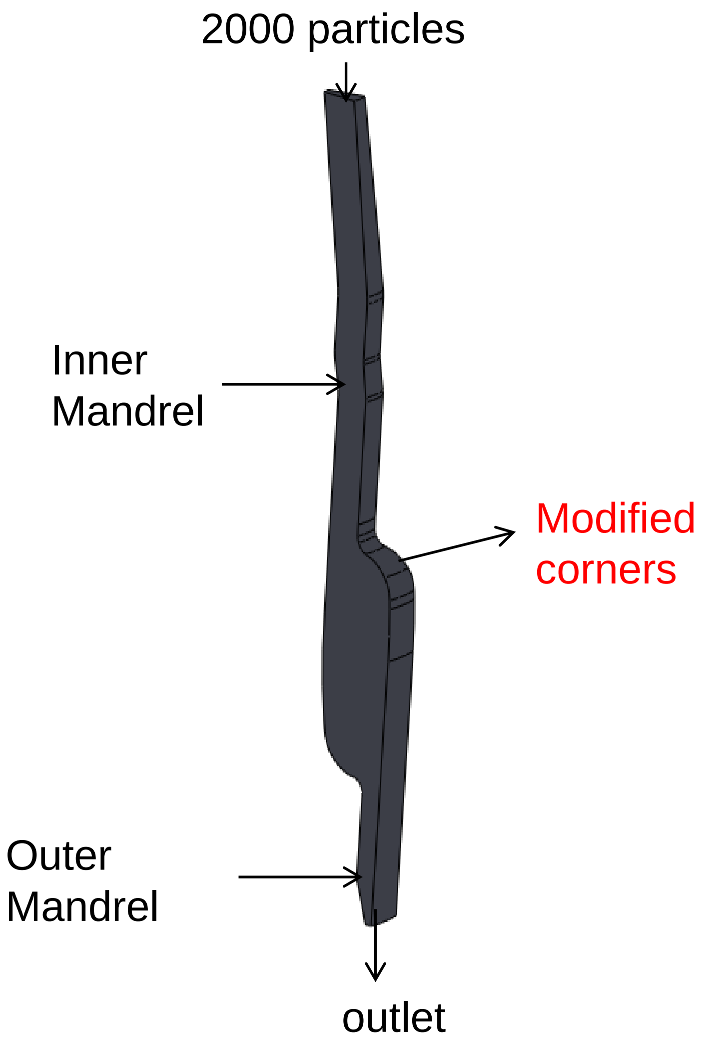


Baseline for the RTD

Die without lattice



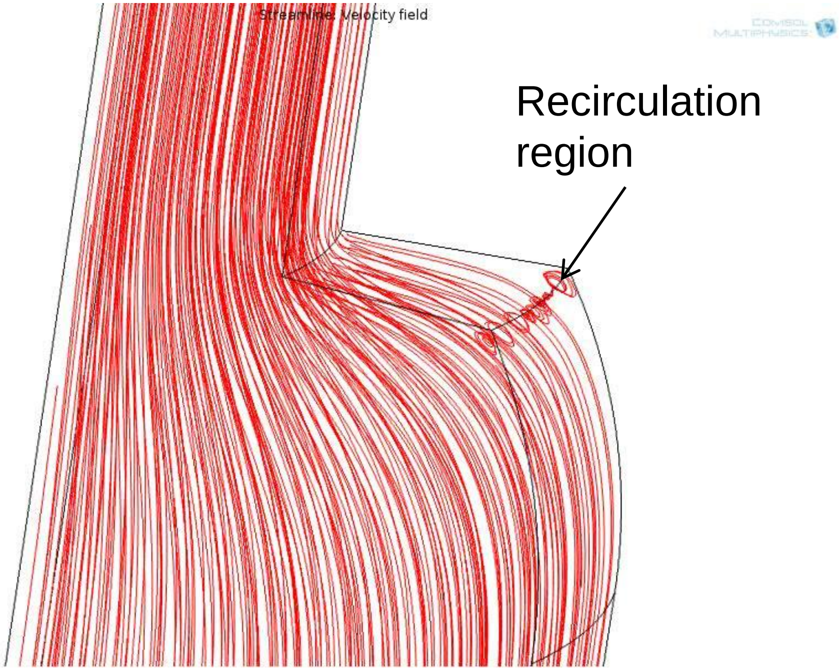
Hypothetical model



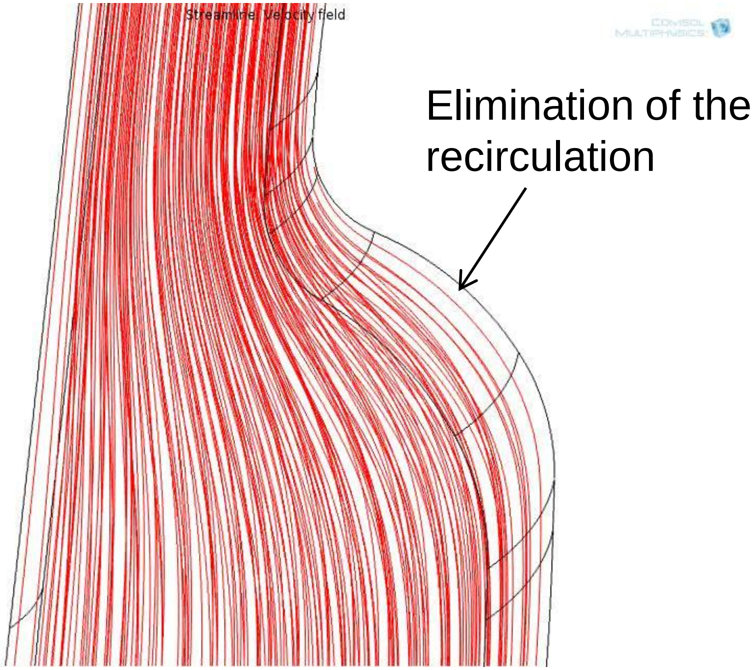
Implication of the mandrels

Streamlines

Die without lattice



Hypothetical model

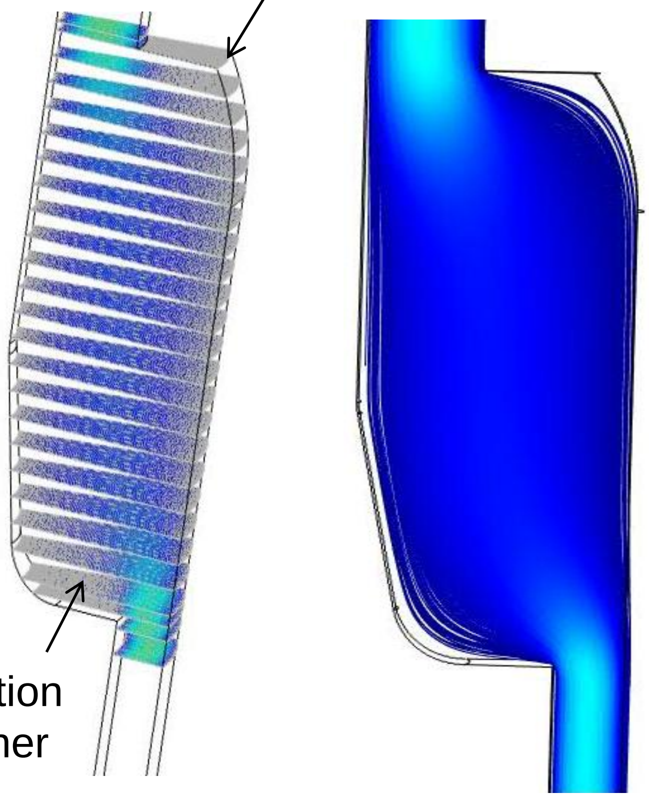


Implication of the mandrels

Particle tracing

Die without lattice

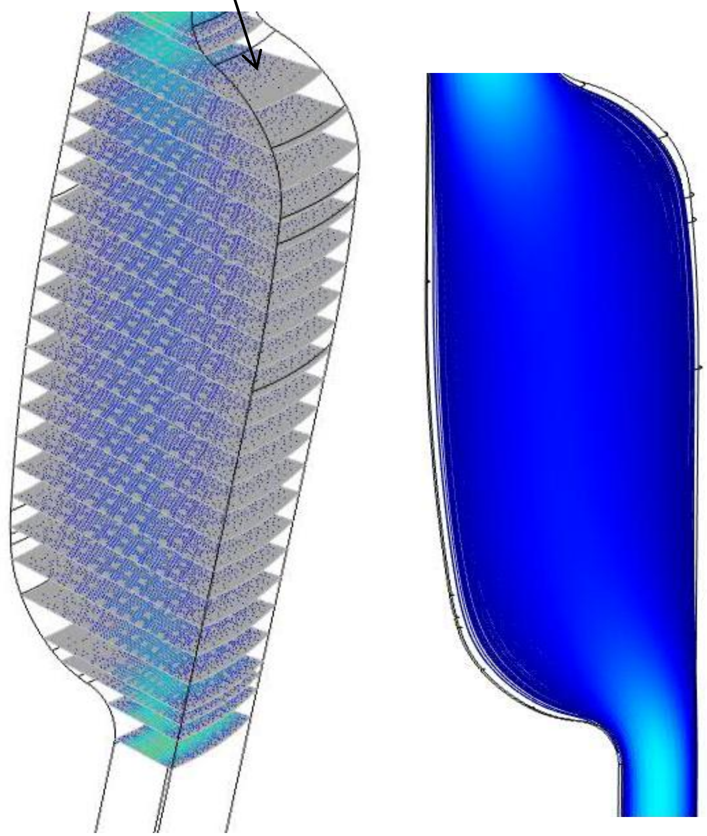
Modification of the outer mandrel



Modification of the inner mandrel

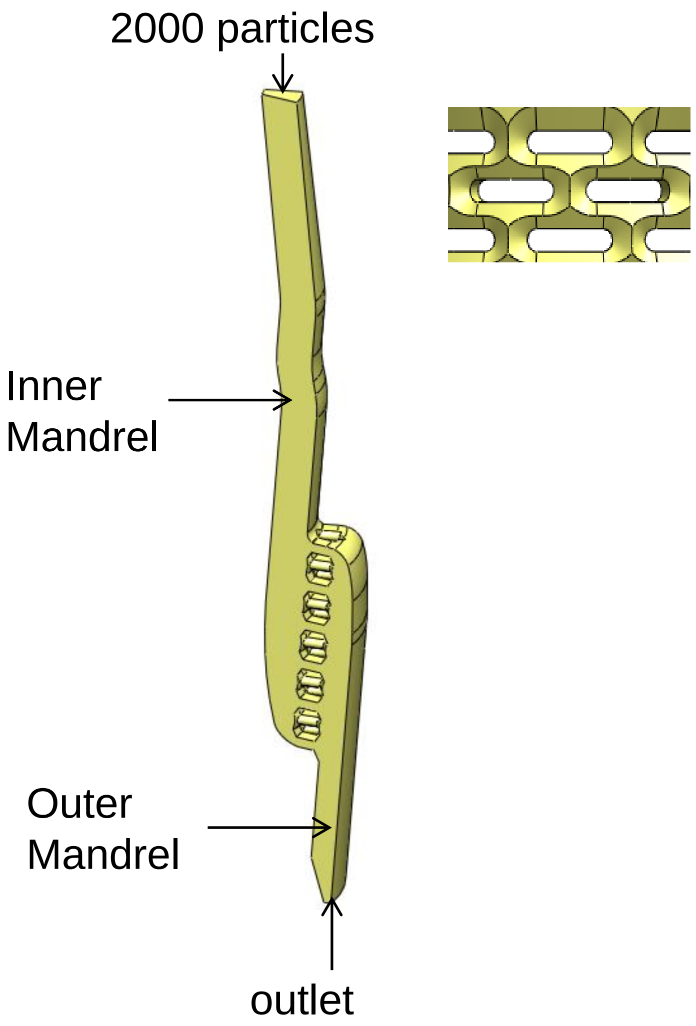
Hypothetical model

Elimination of zero velocity zones

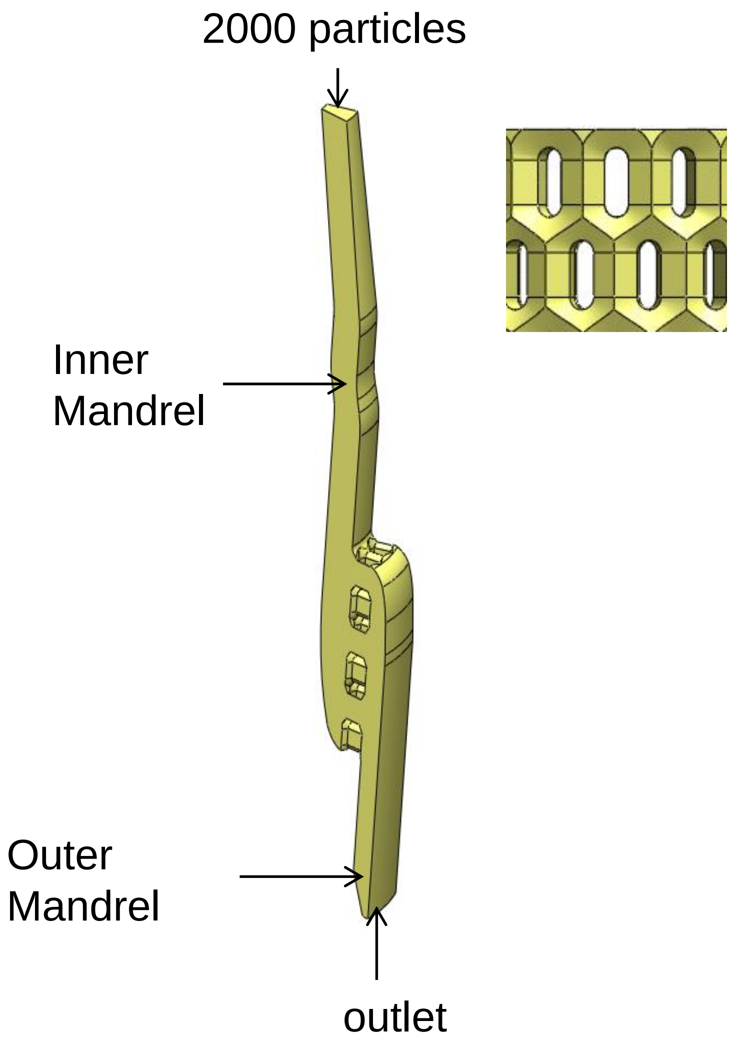


Optimization of the die

Slots in a horizontal fashion



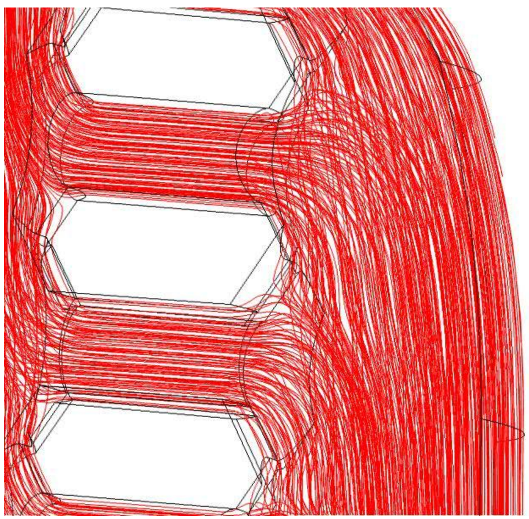
Slots in a vertical fashion



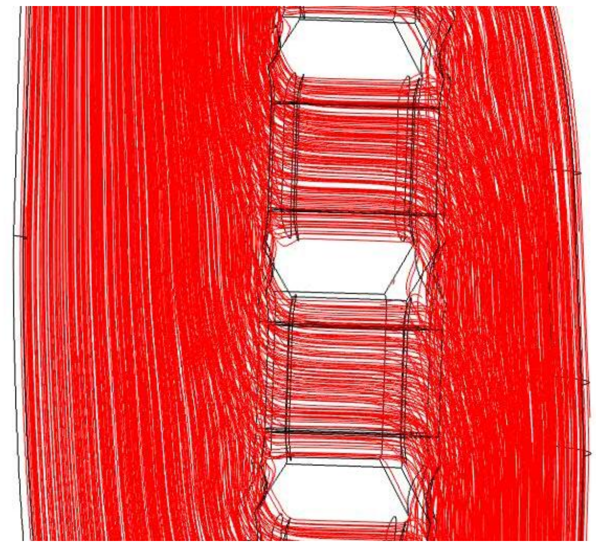
Novel flow channel profiles

Streamlines

Horizontal slots



Vertical slots

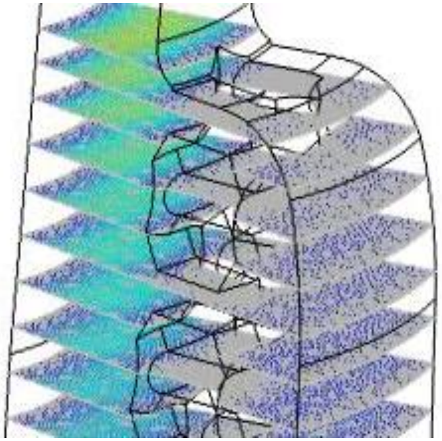


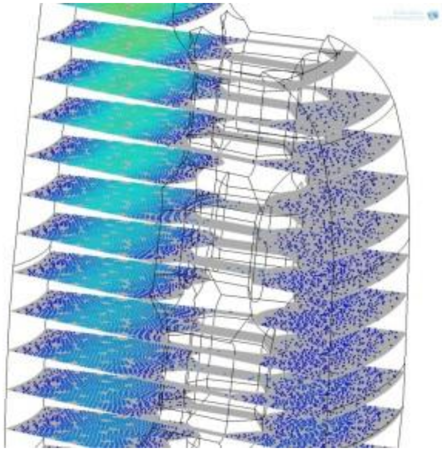
Novel flow channel profiles

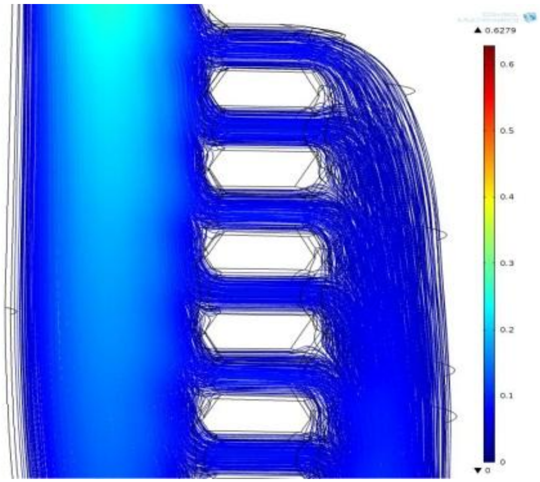
Particle tracking

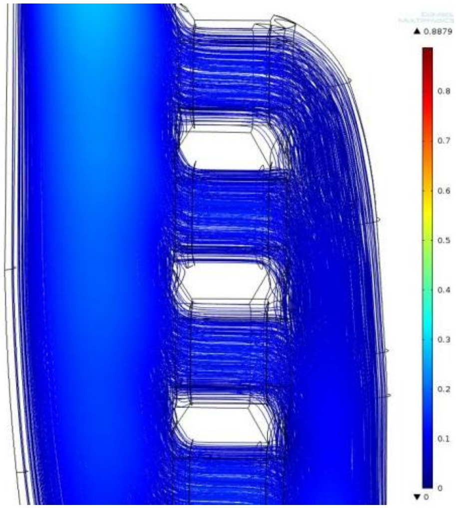
Horizontal pattern

Vertical pattern

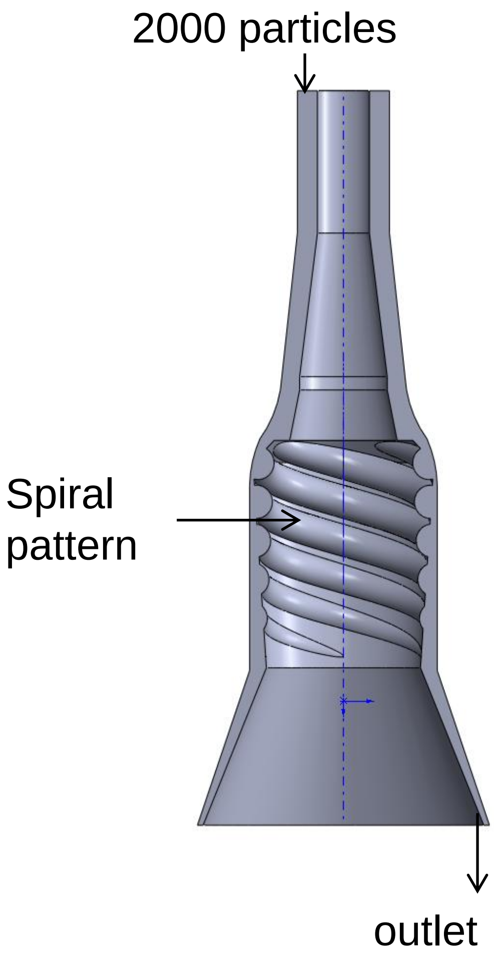


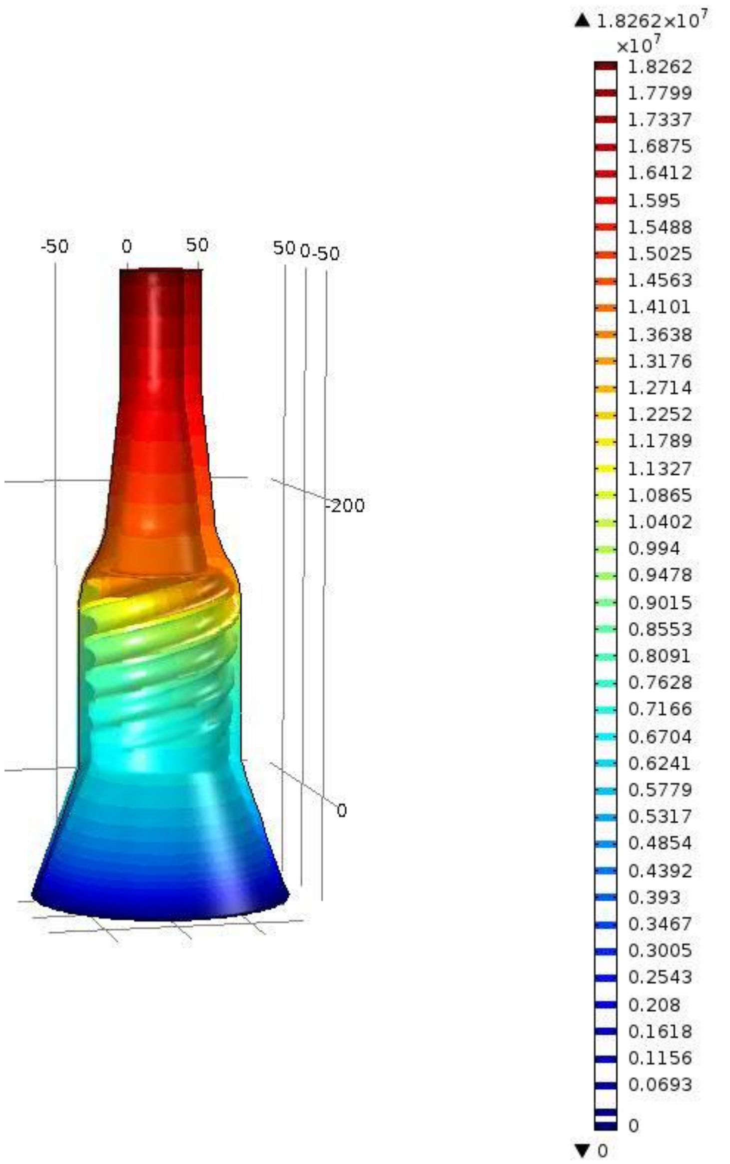






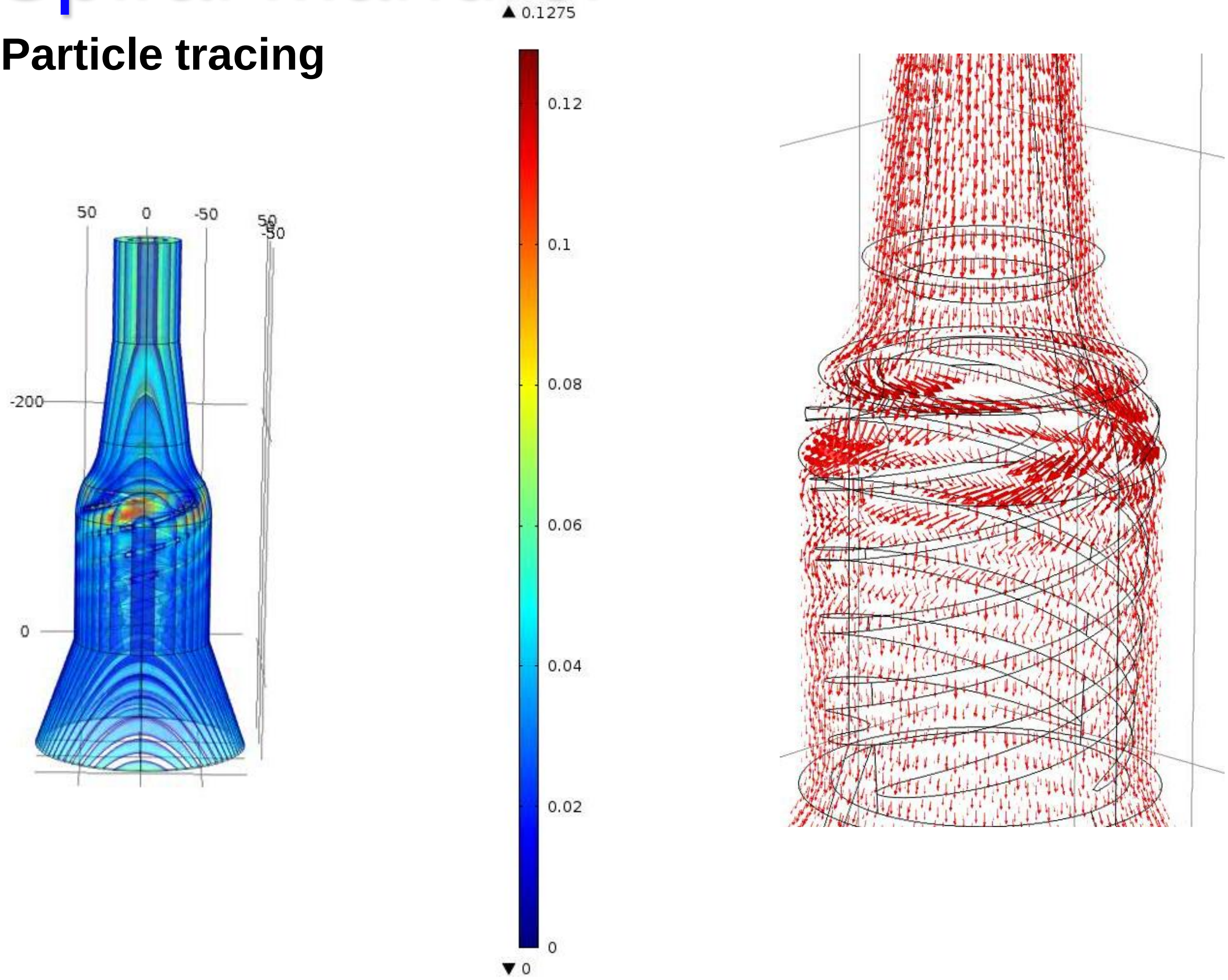
Spiral Mandrel





Spiral Mandrel

Particle tracing

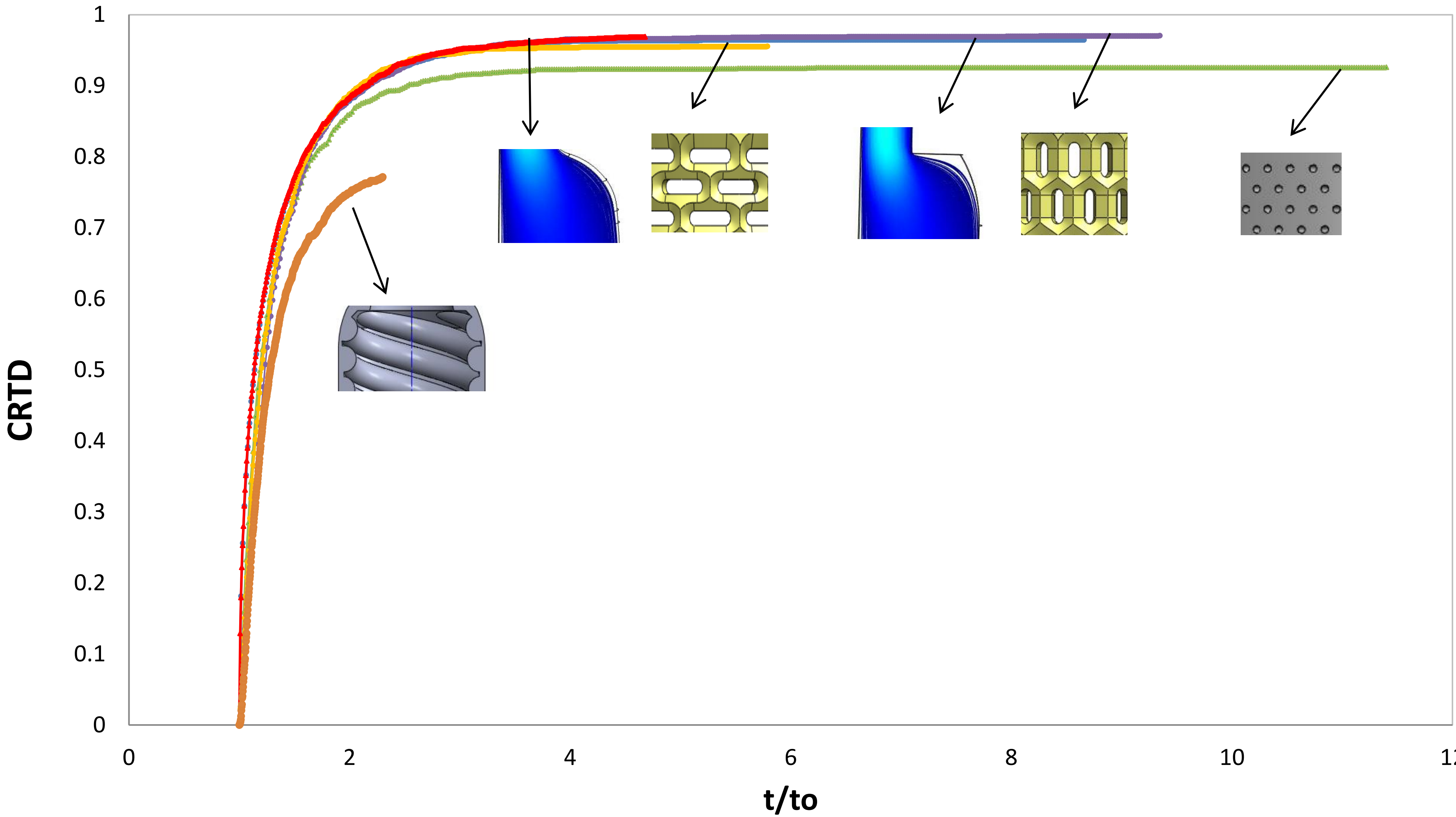


CRTD

$$Transmision\ Probability = \frac{number\ of\ particles\ \ which\ reach\ the\ outlet}{number\ of\ particles\ released}$$

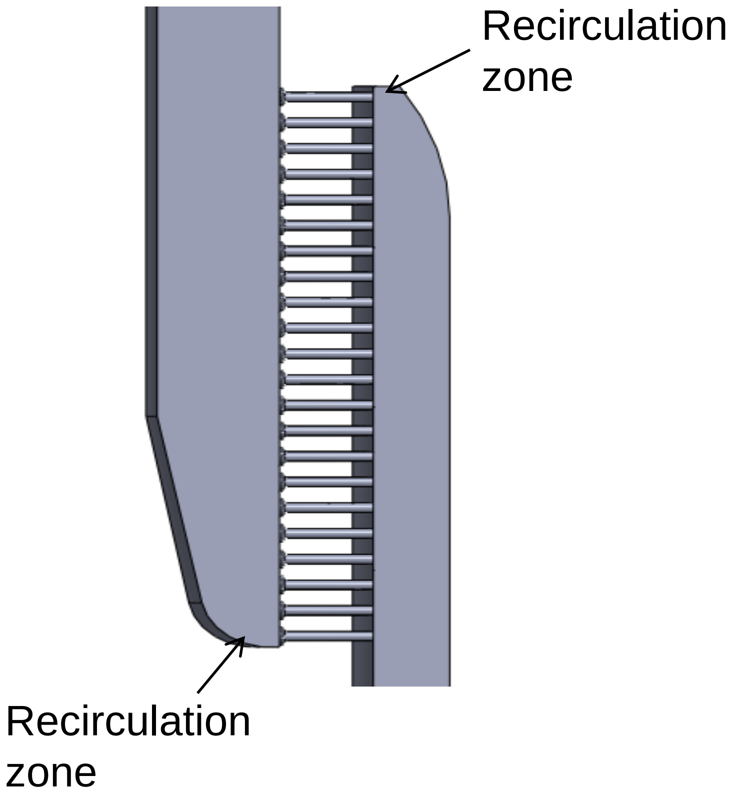
Model	*Number of particles released*	*Particles that reached the outlet*	*Transmission Probability*	*Retained particles*
Lattice basket die	2000	1852	0.91	148
Die without lattice basket	2000	1929	0.9645	71
Hypothetical model	2000	1939	0.9695	61
Slots in a horizontal fashion	2000	1911	0.9555	89
Slots in a vertical fashion	2000	1941	0.9705	59
Spiral Mandrel	2000	1543	0.7715	457

CRTD

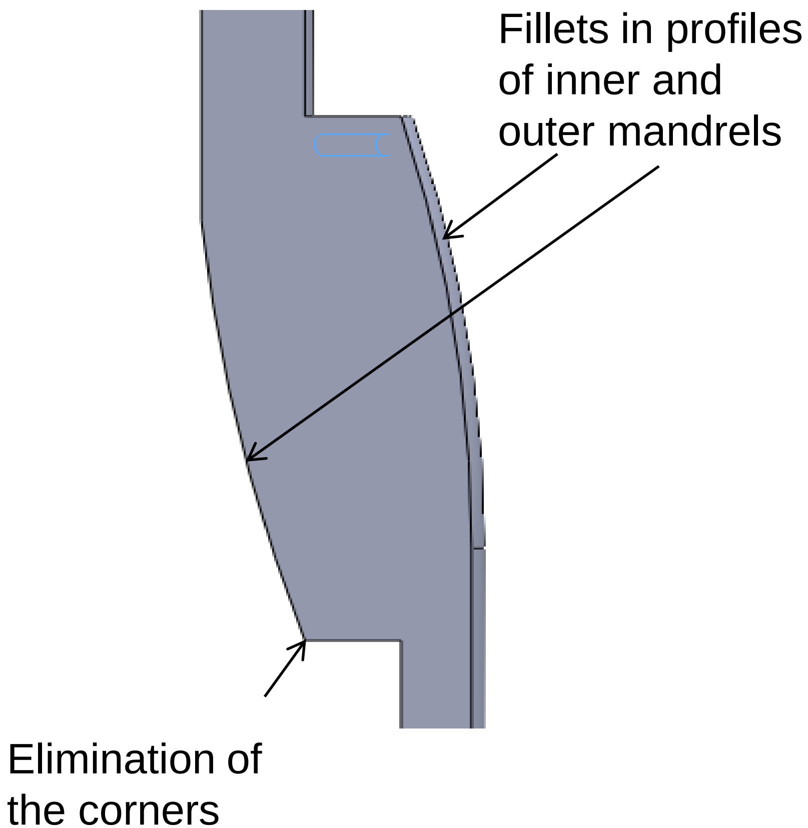


Mechanical Design improvements

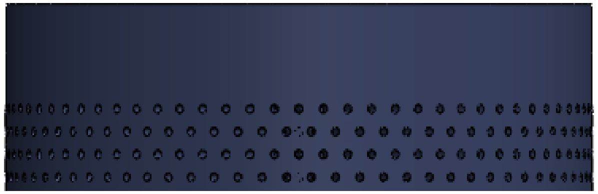
Previous mandrel design



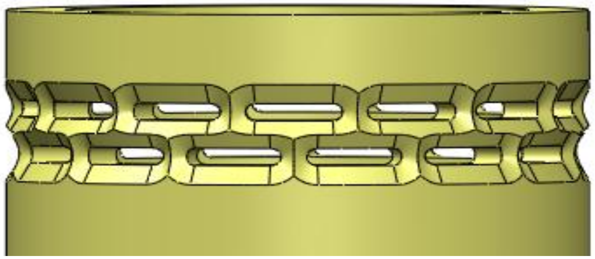
Possible solution

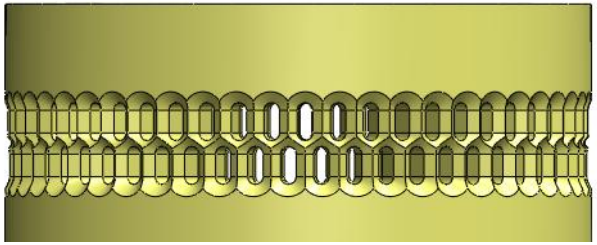


Mechanical Design improvements



Lattice basket





Horizontal Slots

↓RTD 50%

60% less retention of material

Vertical Slots

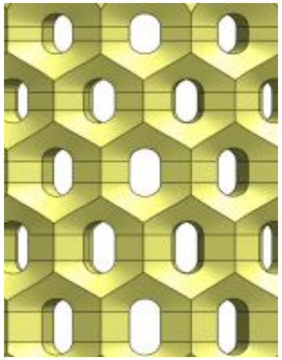
↓ RTD 75%

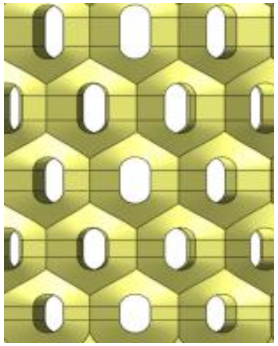
3 times less retention of material

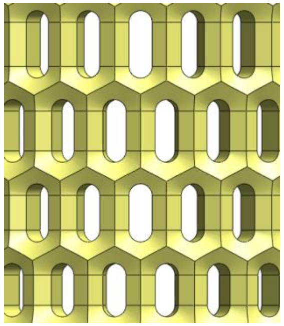
Smaller pressure losses
Lower Power requirements for the same operation conditions
Higher volumetric flow rates

Future Work

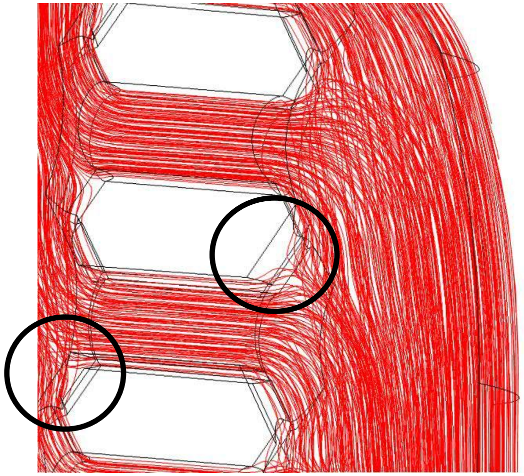
Velocity profile







Structural analysis



Future Work

Isothermal assumption

Analysis of the Brinkman number $Br = \frac{u^2\eta}{k\Delta T}$

Experimentation

Influence of the number of cavities and the area of the cavities in the surface finish and mechanical strength.

Geometry	***Number of cavities***	***Total area (mm^2)***	***Ratio of cavities***	***Ratio of areas***
Lattice basket	2100.00	3.00	1.00	1.00
Vertical slots	550.00	59.63	3.82	19.85
Horizontal slots	126.00	108.63	16.67	36.16
Spiral mandrel	4.00	127.68	525.00	42.50

The authors are grateful to TEEL Plastics Inc. for the technological and financial support in this project.

Thanks to all the members of the PEC

Thanks to technical support of COMSOL Multiphysics.

References

Osswald T. A., J. P. Hernández-Ortiz, “Polymer Processing Modeling and Simulation.” Hanser, Munich (2006).

Osswald T.A., Menges G., Materials of Polymers for Engineers, 2nd Edition, Hanser, Munich (2003). [9]

Michaeli W., Extrusion Dies, 3rd Edition. Hanser, Munich 2003. p 141-228, p 287-331.

Bird, R.B., W. E. Stewart E. N. Lightfoot, “Transport Phenomena 2nd edition.” Jon Riley and Sons, New York (2002).

Tadmor Z.,Gogos C., Principles of Polymer Processing, Wiley, 2nd edition,2006.

Database MOLDEX 3D

http://www.matweb.com/search/datasheetText.aspx?bassnum=PEHM29

S.E. Kadijk, B.H.A.A. Van Del Brule, On the Pressure Dependency of the Viscous of Molten Polymers. Phillips Research Laboratories. Polymer Engineering and Science . October 1994, Vol 34 No 20. 1535-1546