Using OpenFOAM® to Aid the Design of Complex profile Extrusion Dies

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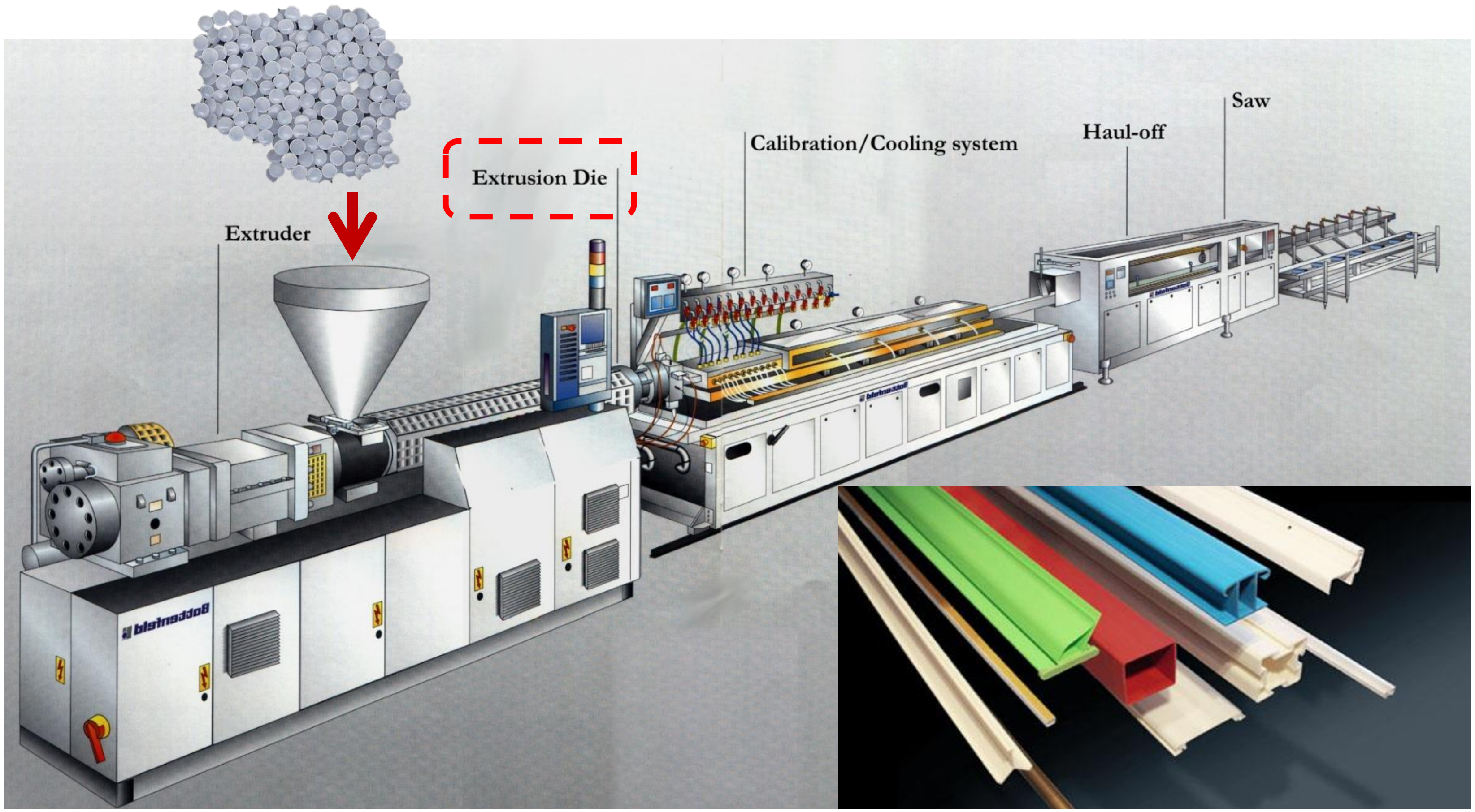
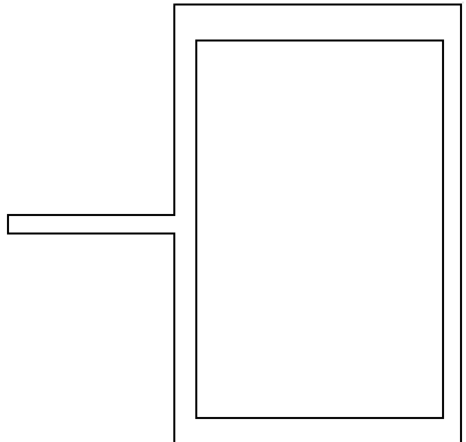
- Motivation
- Numerical Code
- Solver Verification
- Design Procedure
- Case Study
- Conclusion

Profile Extrusion



Profile Extrusion die design



Outlet profile cross section with different wall thicknesses

Flow balancing is more difficult for a complex profile

Unbalanced flow

Balanced flow

Nóbrega, J.M., Carneiro, O.S., Pinho, F.T., Oliveira, P.J. – Flow Balancing in Extrusion Dies for Thermoplastic Profiles. Part **III**: Experimental Assessment, **International Polymer Processing** Vol 19 (2004), p. 225-235;

Complex Profile Extrusion die design

→ Balancing the flow is very difficult

→ High resource consumption (trial-and-error design approaches)

→ highly dependent on designer's experience

Need for an improved numerical approach as an alternate to the usual experimental trial-and-error extrusion die design procedure → OpenFOAM®

Steady state non-isothermal flow of an incompressible GNF

- Mass conservation

$$\frac{\partial u_i}{\partial x_i} = 0$$

- Linear Momentum conservation

$$\frac{\partial p u_j u_i}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x j}$$

$$\tau_{ij} = \eta(\dot{\gamma}) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

- Energy equation

$$\frac{\partial (u_i T)}{\partial x_i} - DT \frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right) = \frac{1}{c} \left(\tau_{ij} \frac{\partial u_i}{\partial x_j}\right)$$

- Constitutive equation

$$\eta(\dot{\gamma}, T) = F\left(\dot{\gamma} \times H(T)\right) H(T)$$

$$F(\dot{\gamma}) = \eta_\infty + \frac{\eta_0 - \eta_\infty}{\left(1 + (\lambda\dot{\gamma})^2\right)^{\frac{1-n}{2}}} \qquad H(T) = \exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right]$$

SimpleFoam + $\eta(T, \dot{\gamma})$ + Energy equation

Methods of Manufactured Solutions (MMS)

1 → **Choose the form of governing equation**

$$\frac{\partial (u_i T)}{\partial x_i} - DT \frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right) = \frac{1}{c}\left(\tau_{ij} \frac{\partial u_i}{\partial x_j}\right)$$

2 → **Choose the form of manufacturing Solution describing the field**

T = 230°C

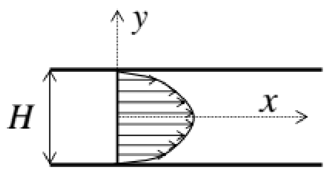
3 → **Generate analytical source term by applying the function to the governing equation**

$$\frac{\partial (u_i T)}{\partial x_i} - DT \frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right) = \frac{1}{c}\left(\tau_{ij} \frac{\partial u_i}{\partial x_j}\right)$$

Methods of Manufactured Solutions (MMS)

$$\frac{\partial(u_i T)}{\partial x_i} - DT\frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right) = \frac{1}{c}\left(\tau_{ij}\frac{\partial u_i}{\partial x_j}\right)$$

$$\tau_{xx}\frac{\partial u}{\partial x}+\tau_{xy}\frac{\partial u}{\partial y}+\tau_{zx}\frac{\partial u}{\partial z}+\tau_{xy}\frac{\partial v}{\partial x}+\tau_{yy}\frac{\partial v}{\partial y}+\tau_{zy}\frac{\partial v}{\partial z}+\tau_{xz}\frac{\partial w}{\partial x}+\tau_{yz}\frac{\partial w}{\partial y}+\tau_{zz}\frac{\partial w}{\partial z}$$



$$\frac{\eta}{c}\left[\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right]\frac{\partial u}{\partial y} \longrightarrow \frac{\eta}{c}\left[\frac{12\,U\,y}{H^2}\right]^2$$

source term

$$u = \frac{3}{2}U\left(1-\left(\frac{2y}{H}\right)^2\right)$$

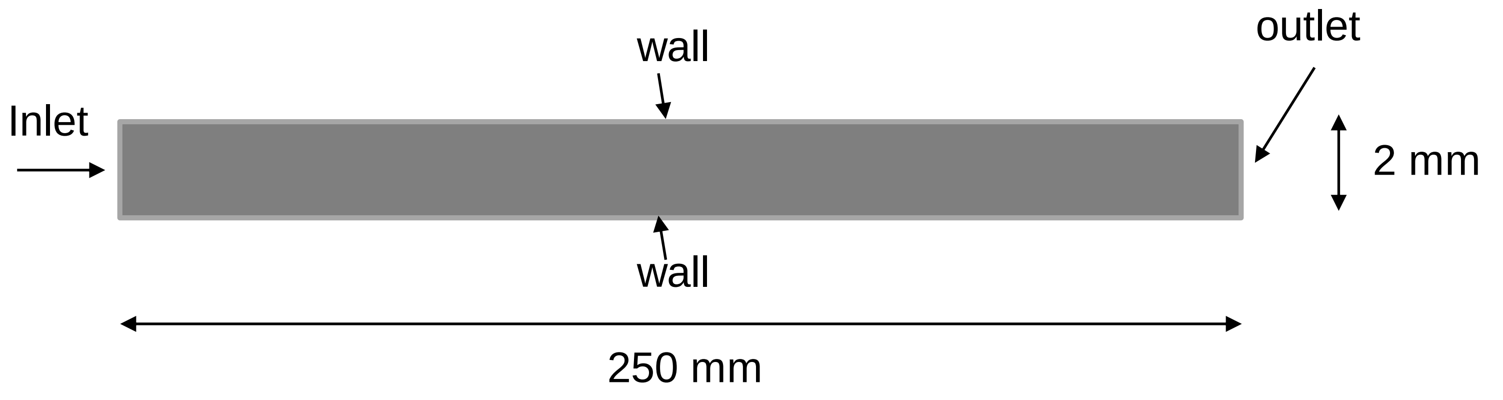
Where U is the mean velocity

4 → **Add the source term to the solver**

5 → **Solve the equations with the source term on multiple computational grids , determine the order of accuracy**

Solver Verification

Reference geometry (2D rectangular channel)



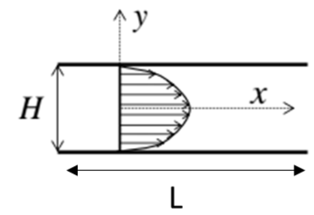
Inlet velocity → fully developed flow (with mean velocity 0.2 m/s)

Temperature at the Inlet and wall = 230 °C

Solver Verification

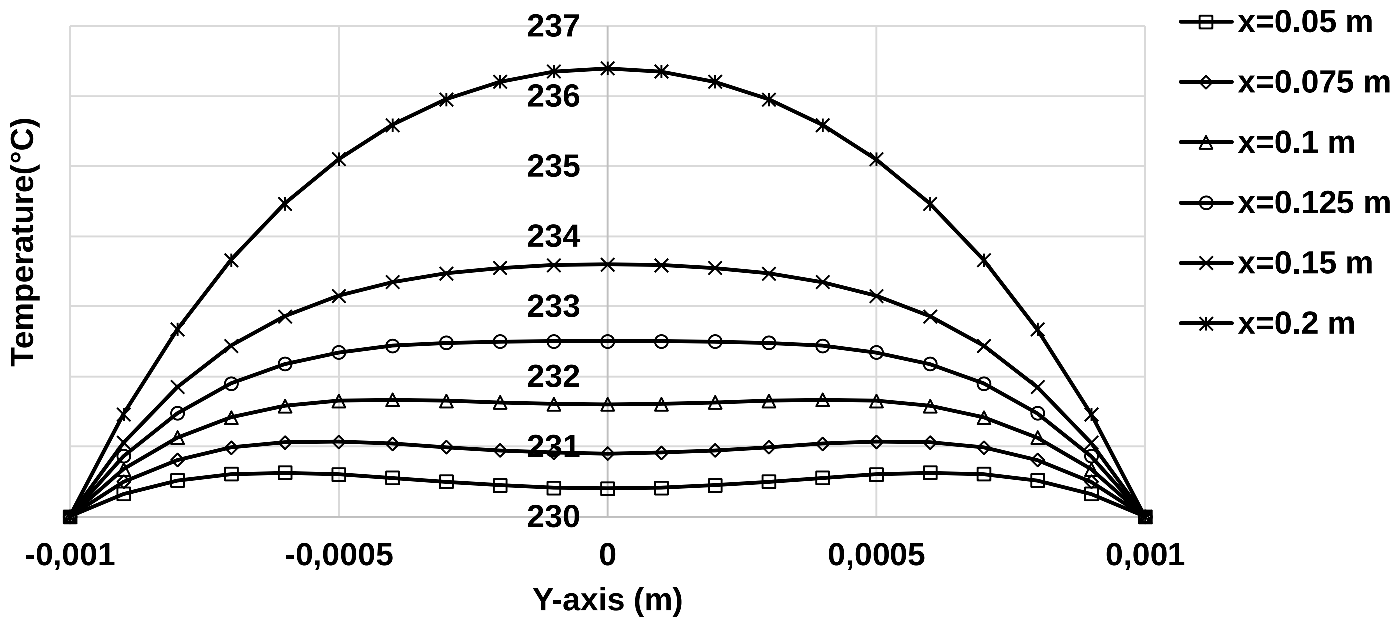
Manufactured solutions employed:

Case 1 : constant temperature = 230 ° C



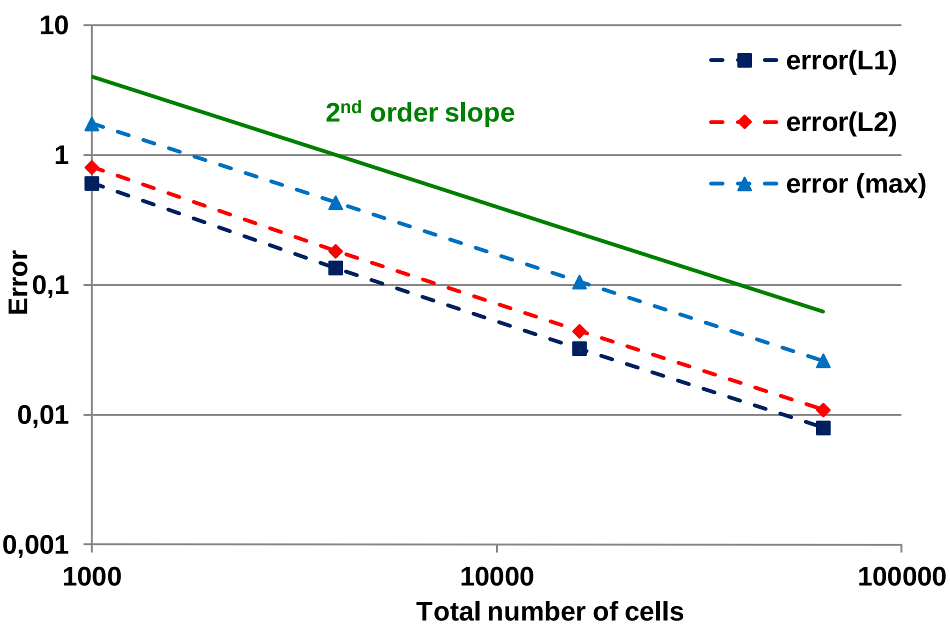
Case 2 : complex Temperature profile

$$f(x,y) = \mathrm{Tw} + \mathrm{Tadd} * (-((1 - x/(L)) * (y * 2/H)\hat{}2 + x/(L)) * ((y * 2/H)\hat{}2 - 1) * x/L$$

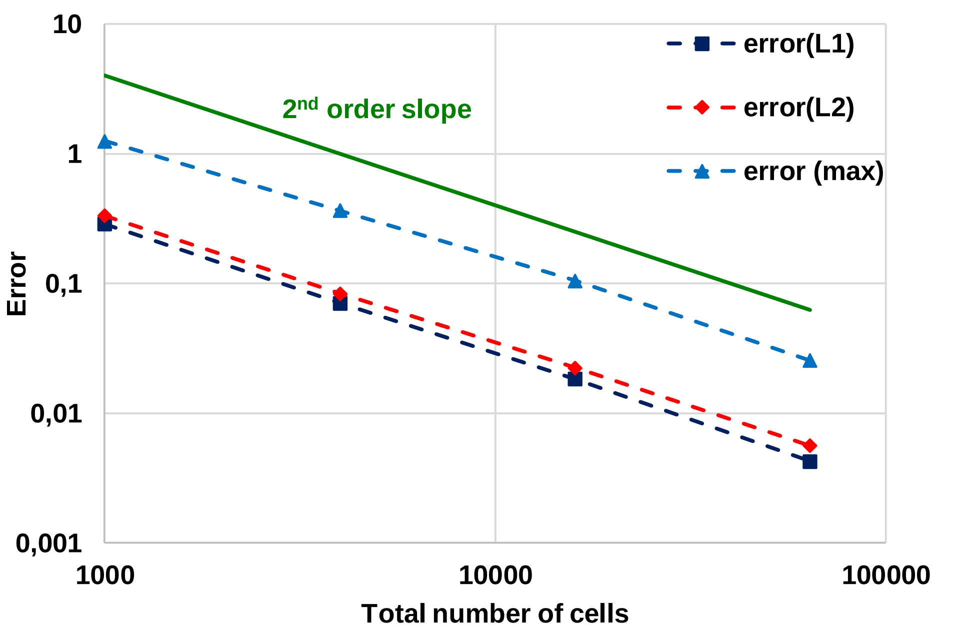


Solver Verification

Case 1 : Manufactured solution (constant temperature = 230 ° C)



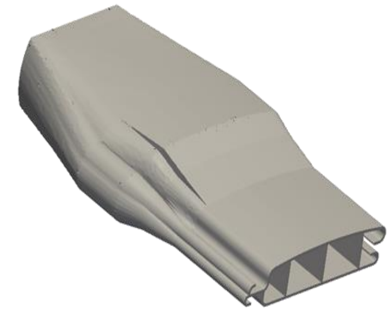
Case 2 : Manufactured solution (complex Temperature profile)



Design Procedure

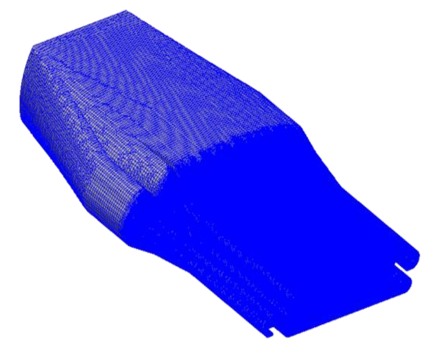
Material characterization → To obtain rheological parameters

CAD Software (Solid works) → Geometry generation and division of sections in the outlet cross section →

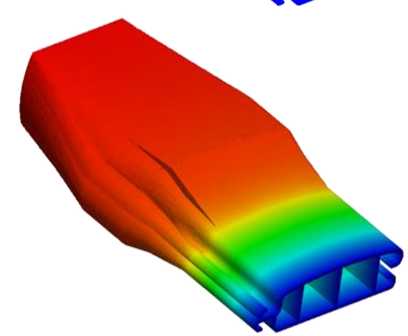


Salome → Defining regions in the geometry , to specify boundary conditions

SnappyHexMesh → Mesh generation →



OpenFOAM → 3D flow field calculation →

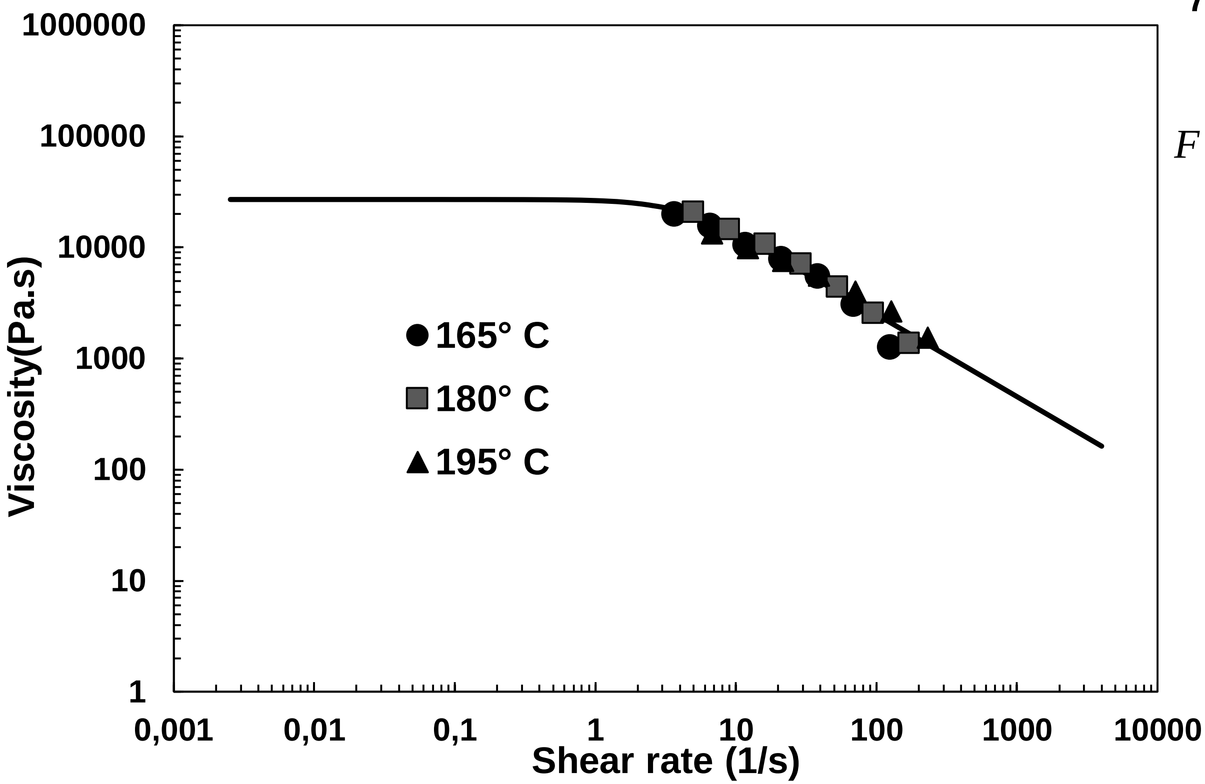


Unbalanced die ← ? → Balanced die

Material characterization

- rheological characterization was performed with a rigid PVC material , at three different temperature , (165 , 180 and 195°C).

the experimental data, fits to a Bird carreau model



$$\eta(\dot{\gamma},T) = F\left(\dot{\gamma} \times H(T)\right)\, H(T)$$

$$F(\dot{\gamma}) = \eta_\infty + \frac{\eta_0 - \eta_\infty}{\left(1+(\lambda\dot{\gamma})^2\right)^{\frac{1-n}{2}}}$$

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

$$\eta_0 = 27000 \text{ Pa.s}$$

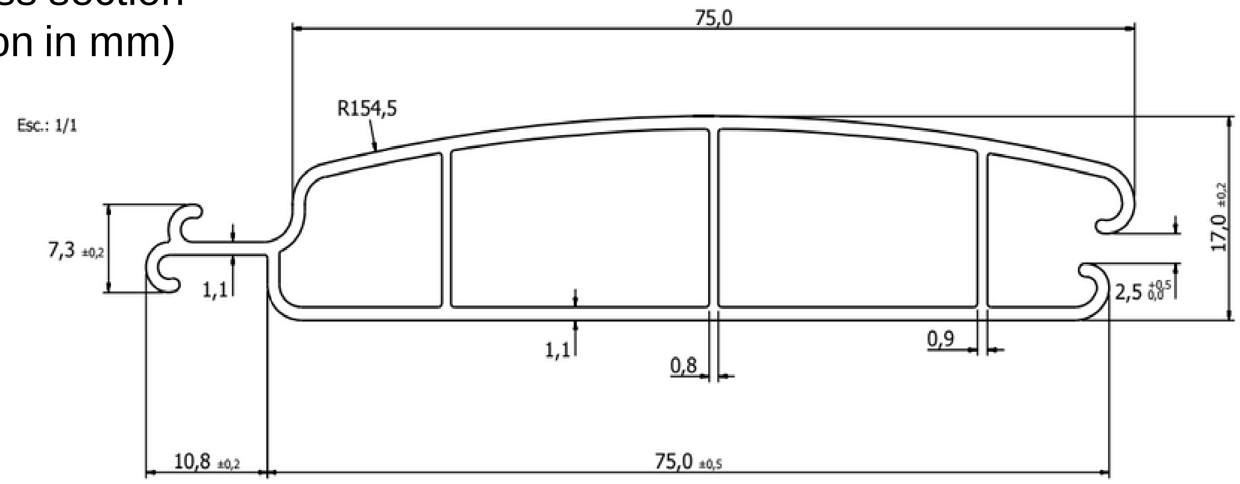
$$\eta_\infty = 0 \text{ Pa.s}$$

$$\lambda = 0.25 \text{ s}$$

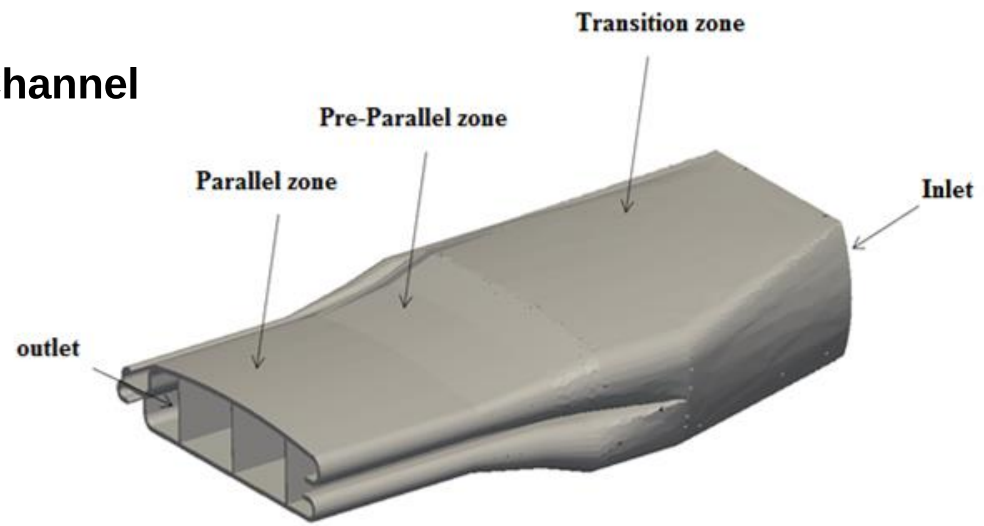
$$n = 0.26$$

$$\alpha = 4209.52 \text{ K}$$

Profile cross section
(dimension in mm)

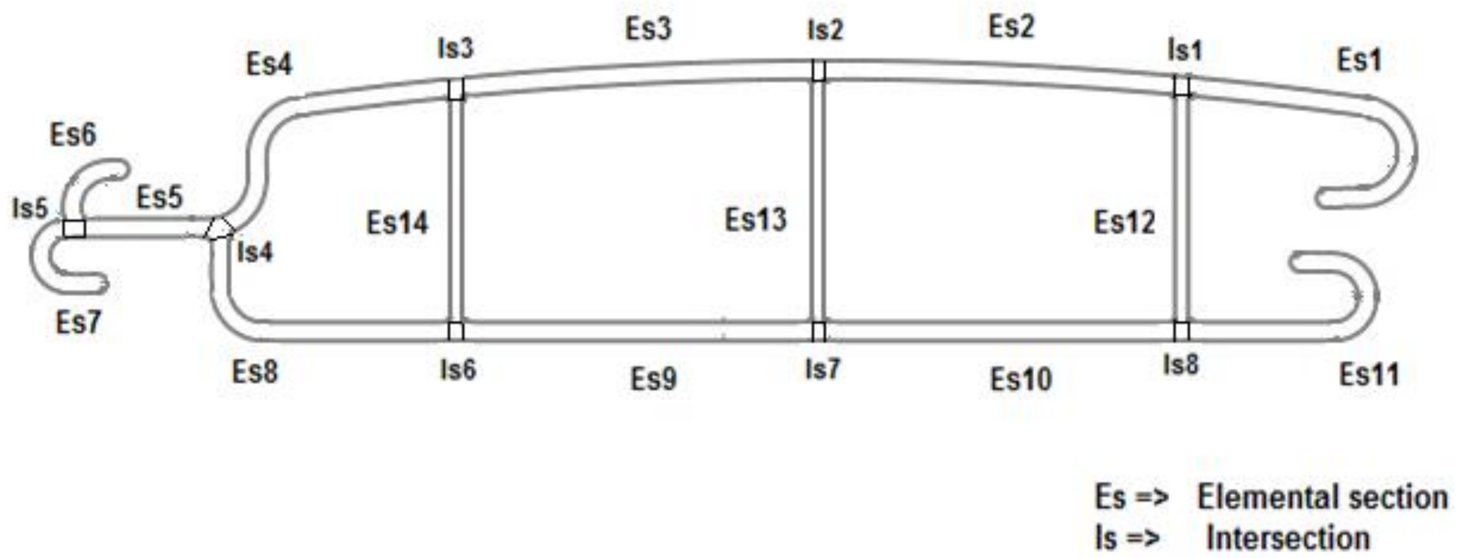


Extrusion Die Flow Channel



Objective: design the flow channel to promote a flow distribution that allows the production of the actual profile

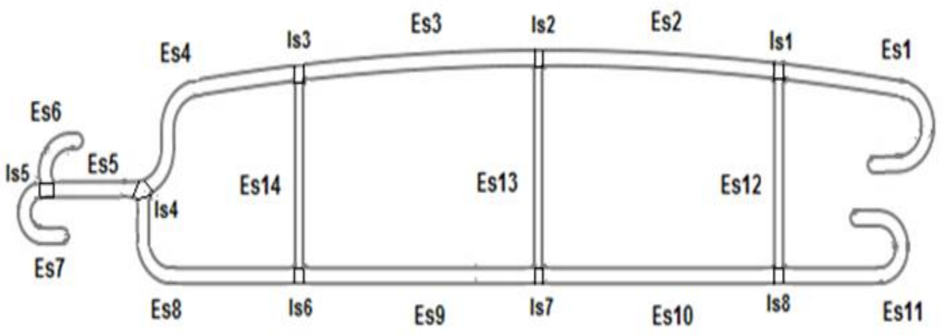
Division of outlet cross section into Elemental sections (ESs) and Intersection(Is), to monitor the flow distribution



Processing Parameters

- outlet velocity 2 m/min
- Temperature at the inlet and walls 180° C

Trial 0


Es3
Is2
Es2
Is3
Is1
Es4
Es1
Es6
Is5
Es5
Es14
Es13
Es12
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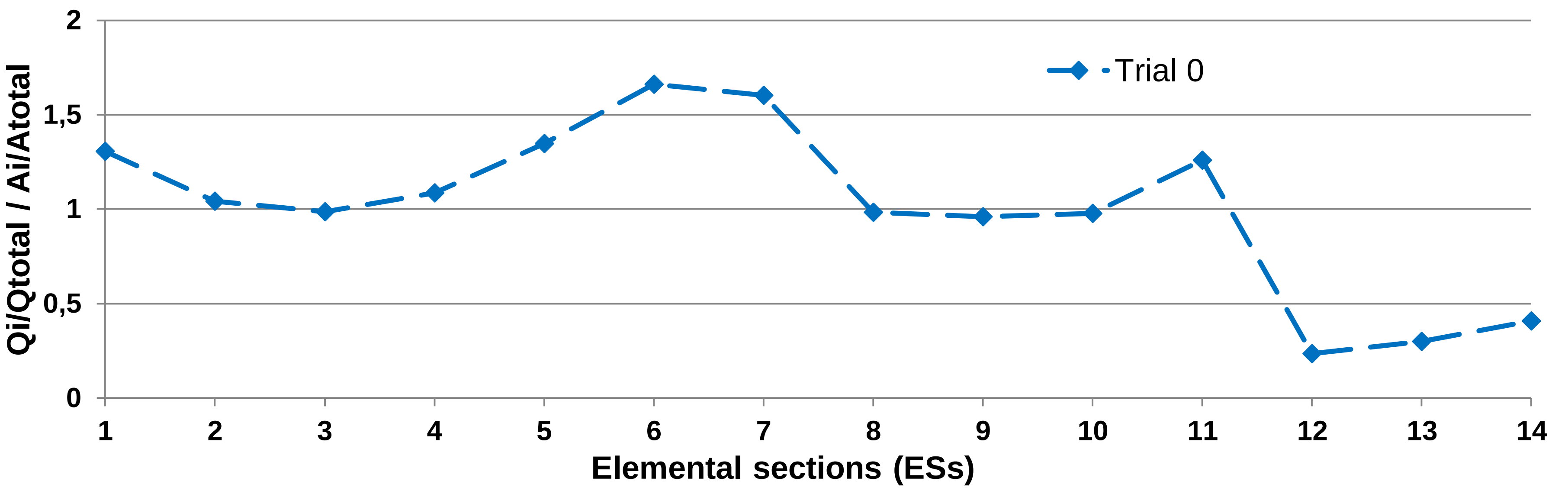
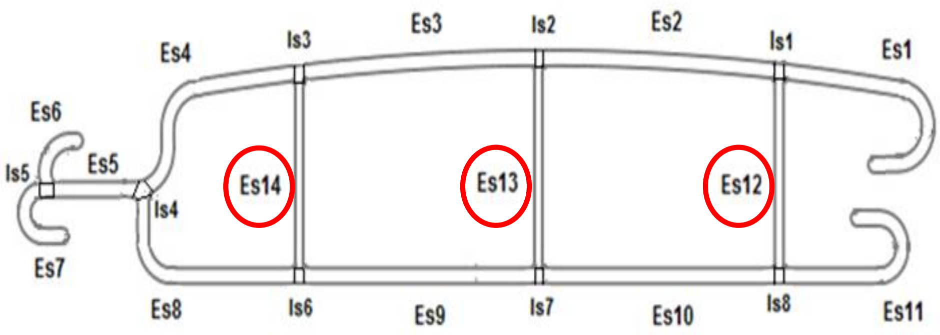
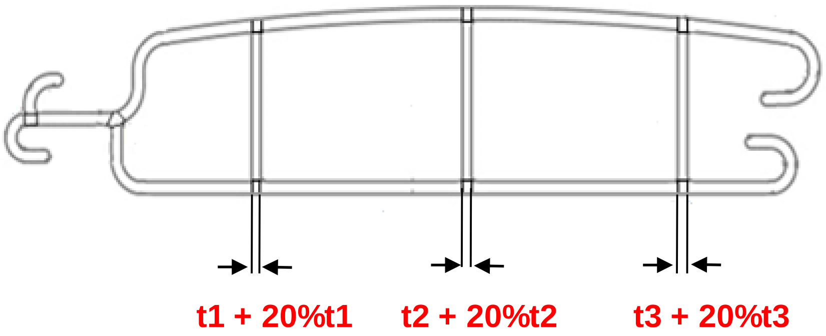
Is6
Es9
Is7
Es10
Is8
Es11

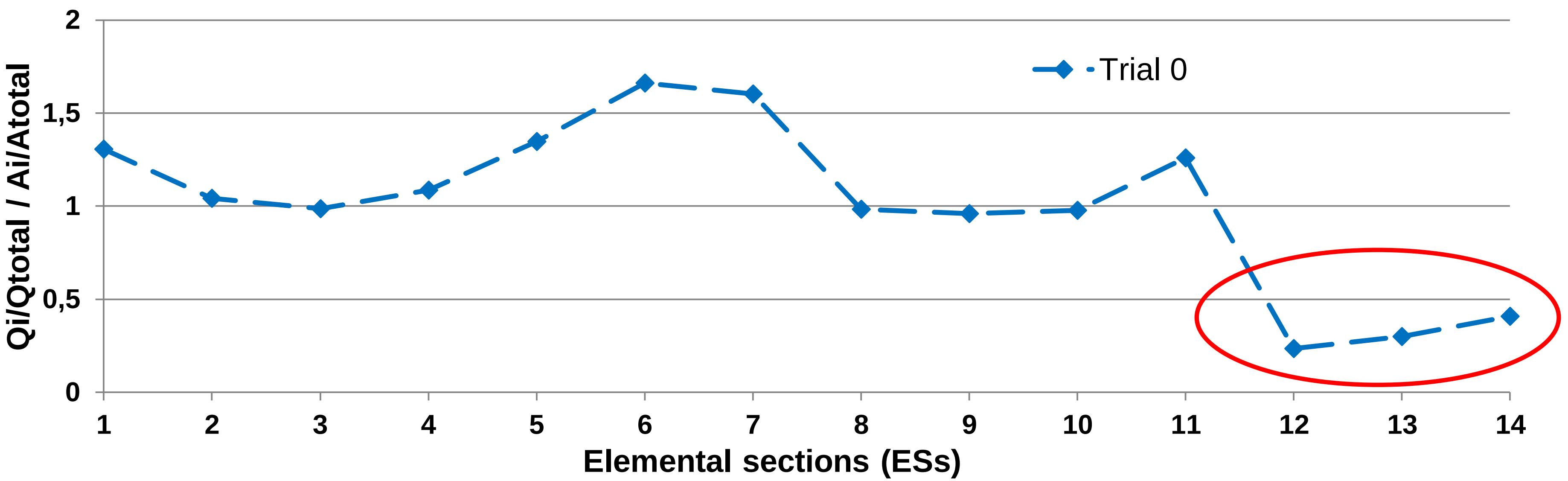

Trial 0
Qi/Qtotal / Ai/Atotal
2
1,5
1
0,5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Elemental sections (ESs)

Trial 0

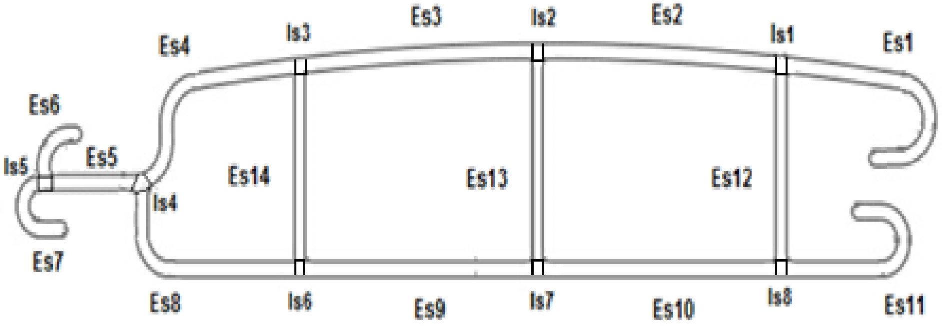


Trial 1





Trial 1


Es3
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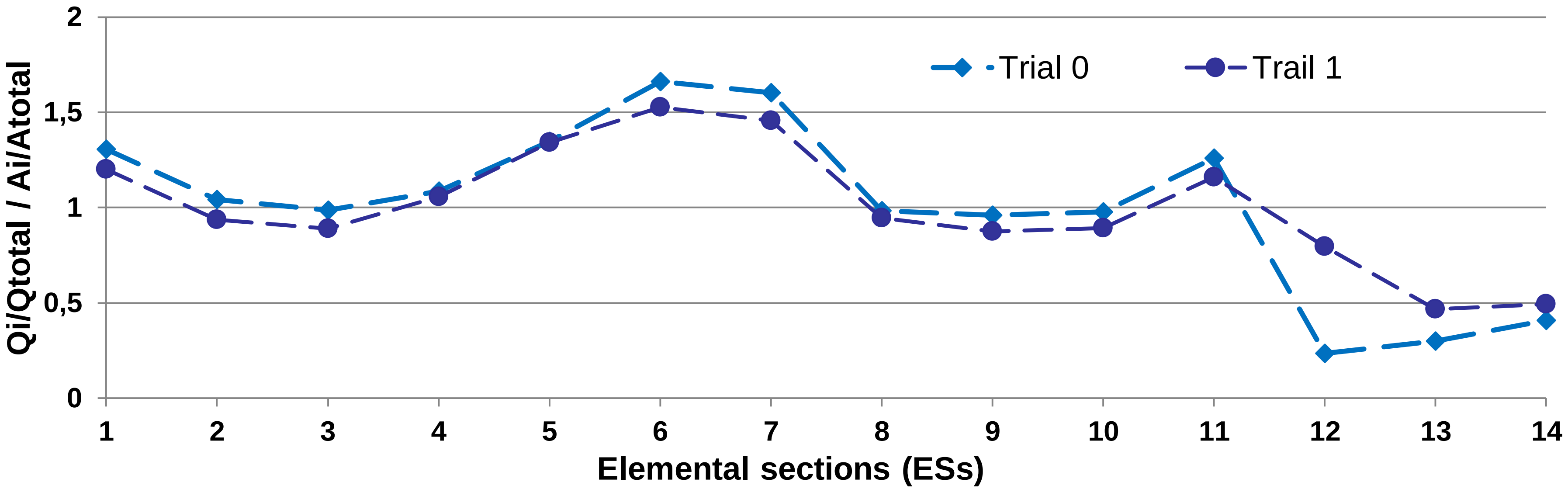
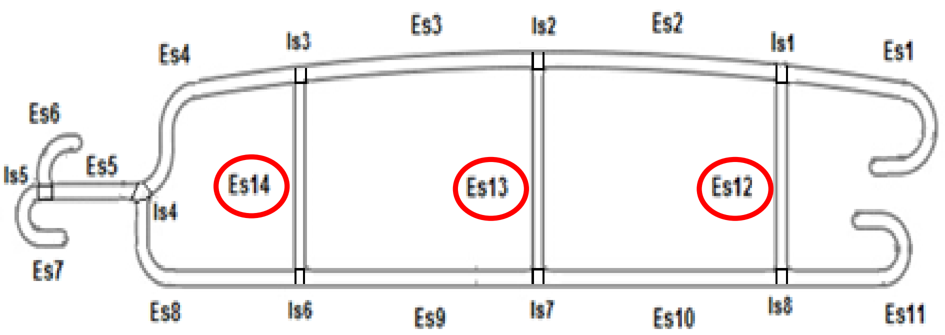
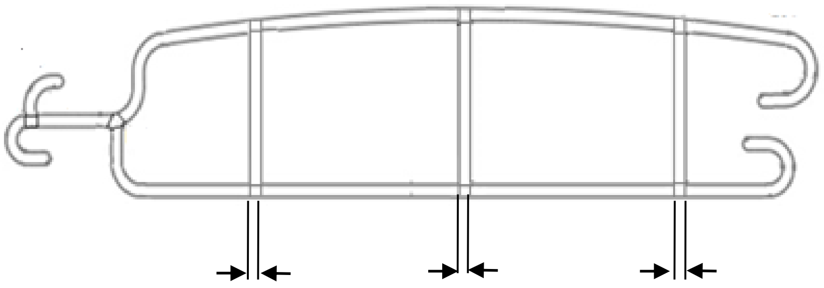
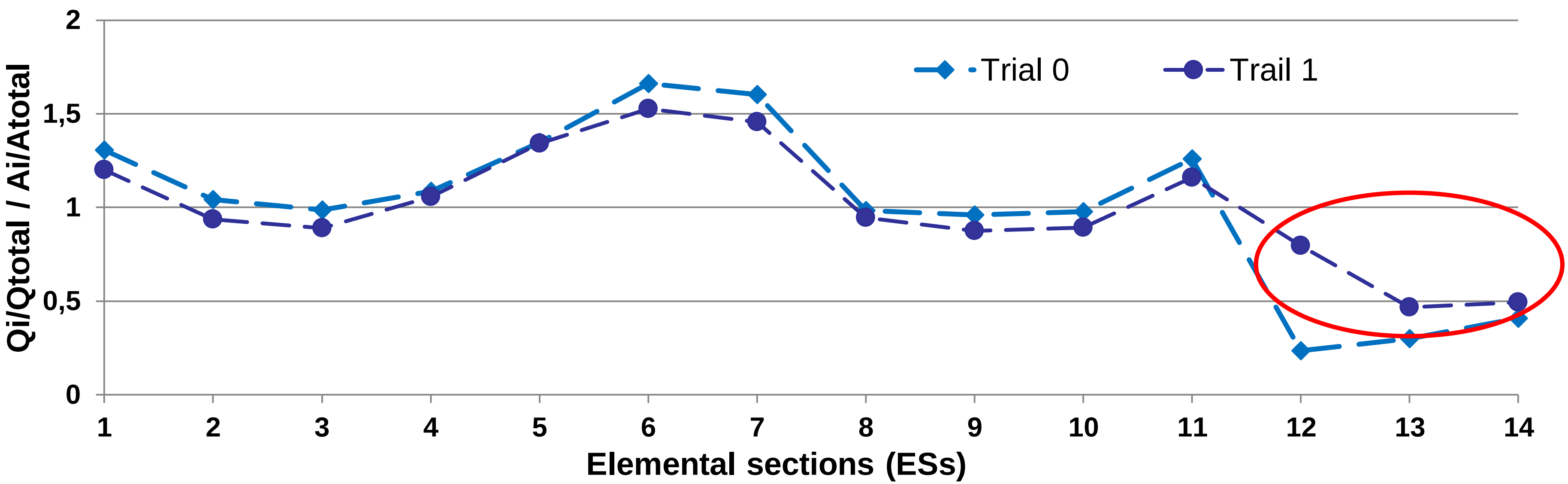

Trial 0
Trail 1
Qi/Qtotal / Ai/Atotal
Elemental sections (ESs)
0
0,5
1
1,5
2
1 2 3 4 5 6 7 8 9 10 11 12 13 14

Trial 1

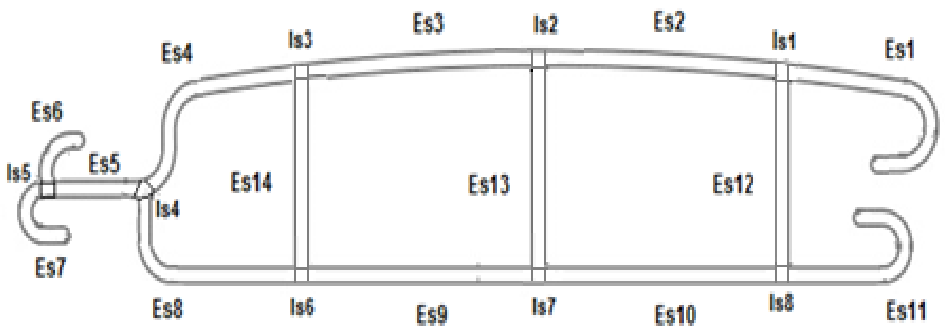


Trial 2





Trial 2


Es3
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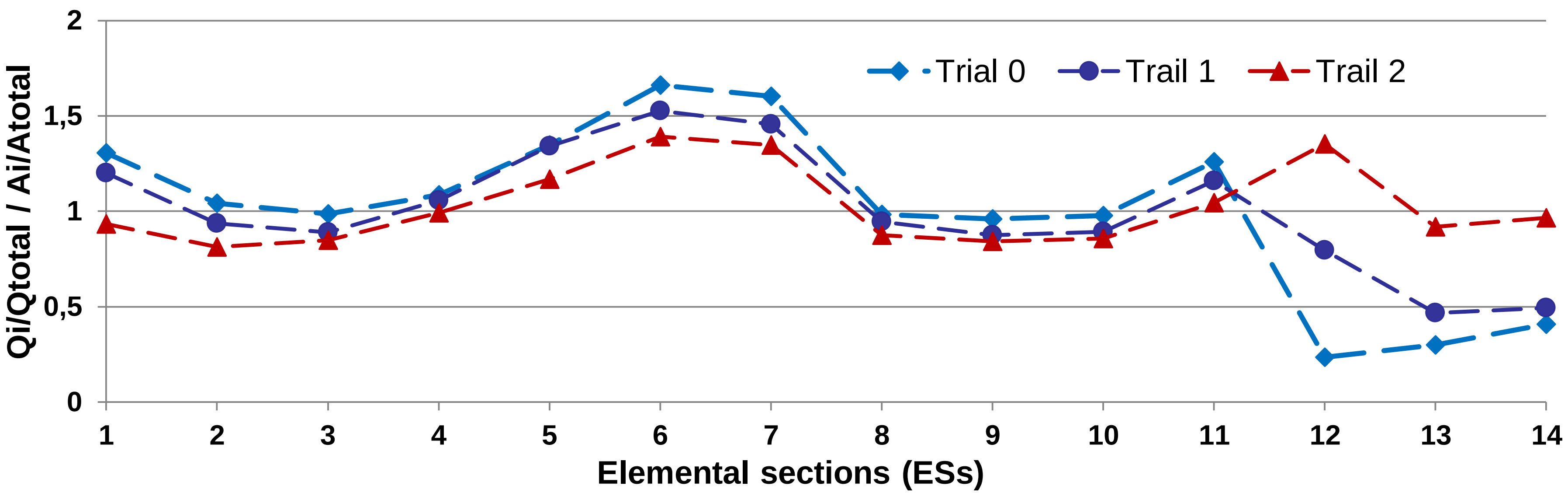
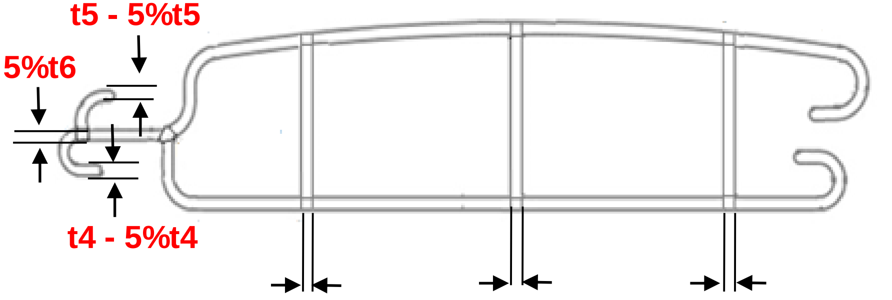
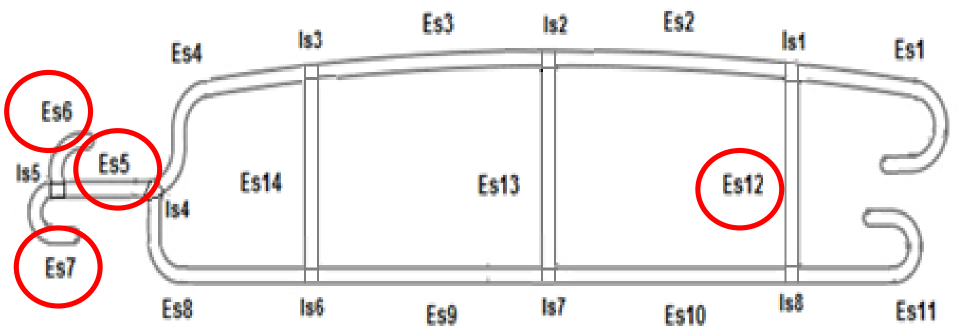
Es11

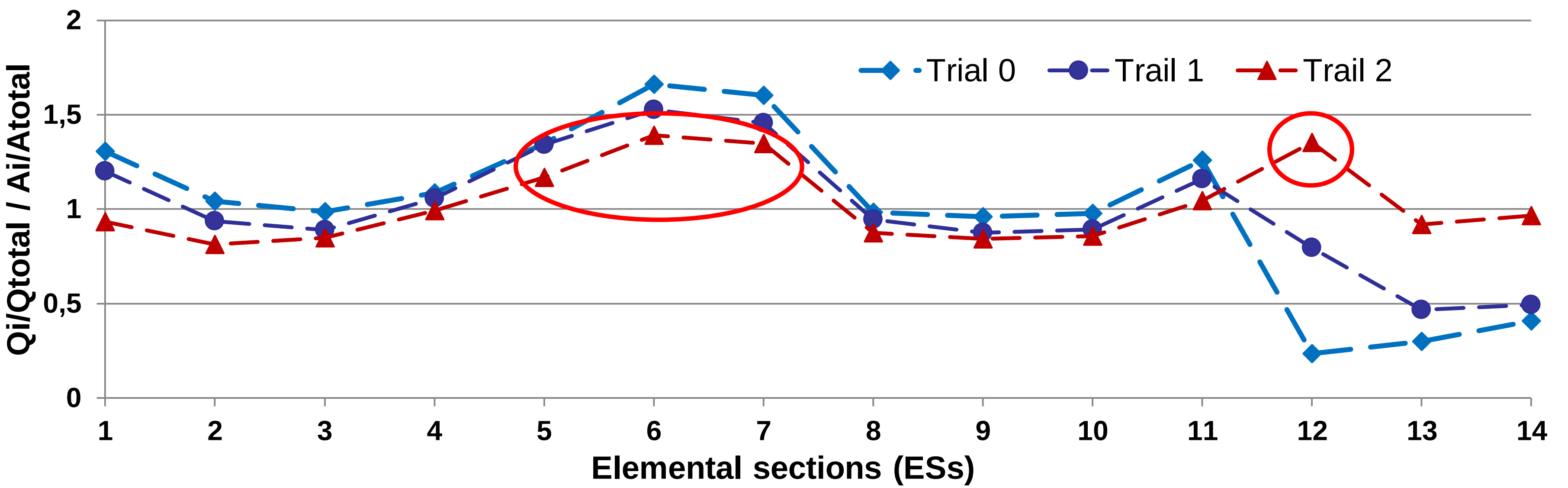

Trial 0
Trail 1
Trail 2
Qi/Qtotal / Ai/Atotal
Elemental sections (ESs)
0
0,5
1
1,5
2
1 2 3 4 5 6 7 8 9 10 11 12 13 14

Trial 3

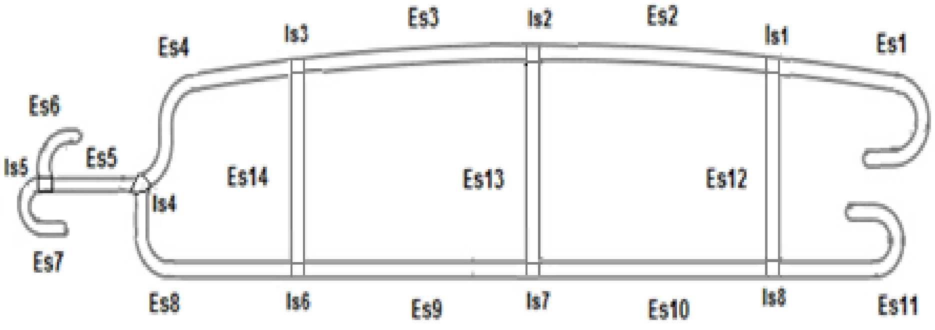


Trial 2





Trial 3


Es3
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Es2
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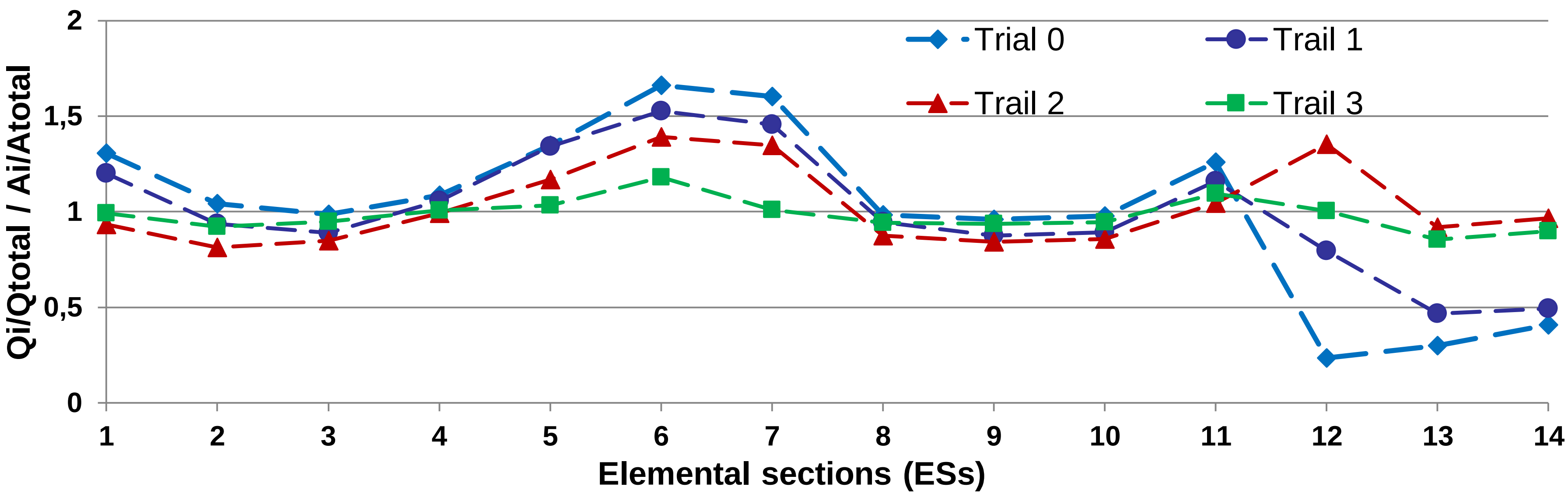
Trial 0
Trail 1
Trail 2
Trail 3
Qi/Qtotal / Ai/Atotal
2
1,5
1
0,5
0
1
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3
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12
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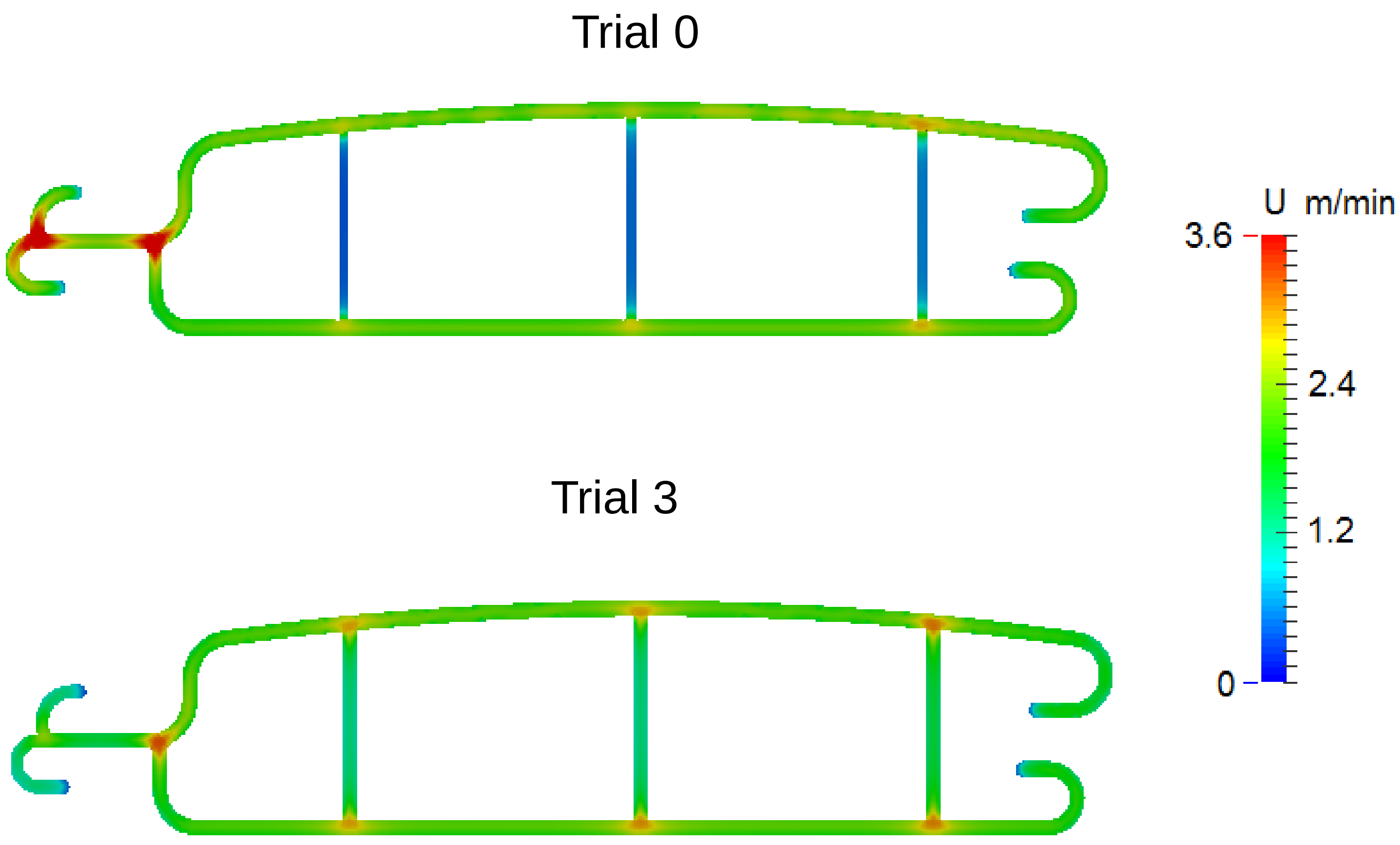
14
Elemental sections (ESs)

Velocity contour (at the flow channel outlet)



- A new OpenFOAM solver able to cope with non-isothermal steady state flows of GNF was implemented
- The new solver was verified with the Method of Manufactured Solutions
- New methodology to design complex profile extrusion dies in OpenFOAM framework was proposed
- The die design methodology was assessed with a complex profile extrusion die

Thanks for your attention!