Development of a new 3D OpenFOAM® solver to model the cooling stage in profile extrusion

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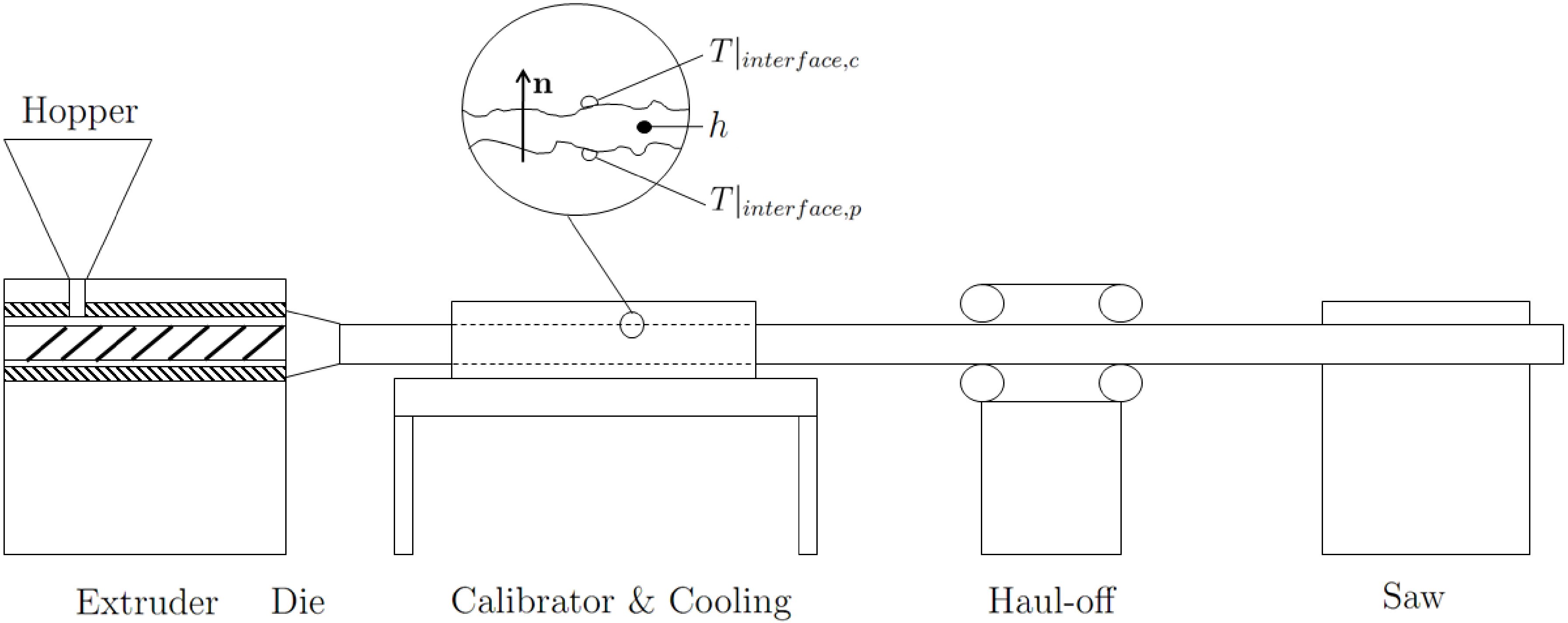
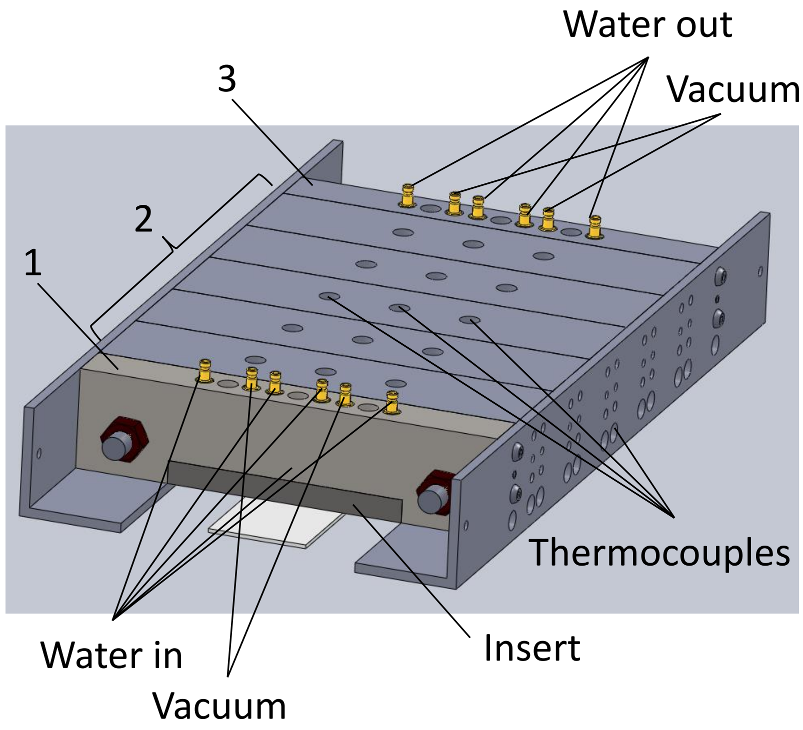
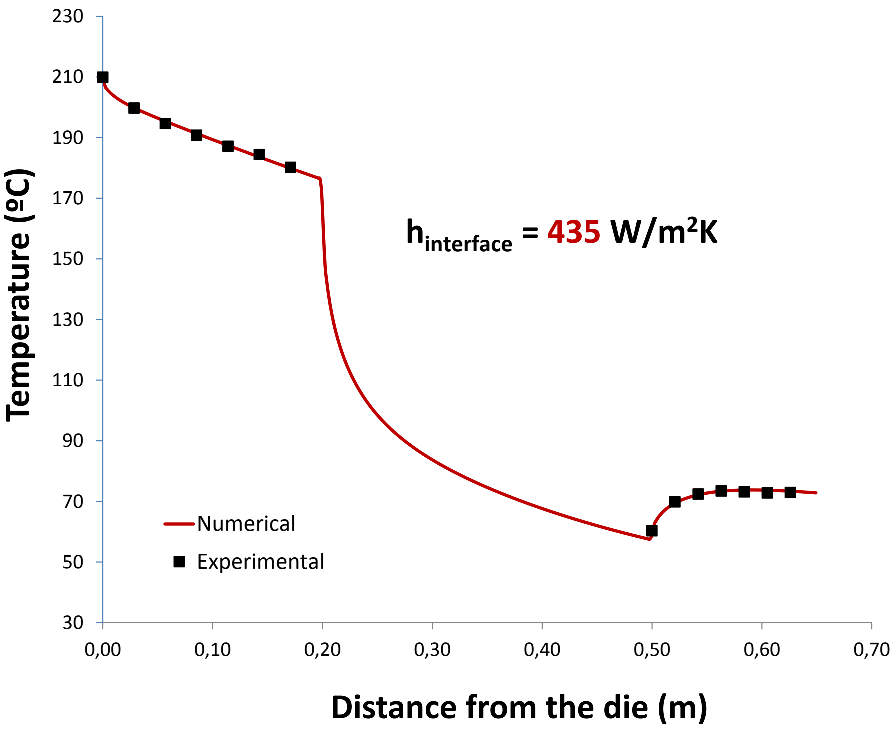
1. Introduction & Motivation



1. Introduction & Motivation





CARNEIRO, O. S. et al. **Polymer Testing.** Vol. 32 (2013), p. 1154-1161

CARNEIRO, O. S. et al. **PT Patent** no. 106368, 2014

1. Introduction & Motivation

- To develop a new solver, in the OpenFOAM® computational library, to model the cooling stage in profile extrusion, using unstructured meshes
- To validate the solver and to access its potential to facilitate the design of industrially relevant profile calibrators

2. Implementation & Verification

$$\frac{\partial(\rho_i c_{P,i} T_i)}{\partial t} + \nabla \cdot (\mathbf{U}_i \rho_i c_{P,i} T_i) - \nabla \cdot (k_i \nabla T_i) = 0 \qquad (1)$$

- **Perfect thermal contact** at the polymer-calibrator interface

$$T\Big|_{interface,p} - T\Big|_{interface,c} = 0 \qquad (2)$$

$$(\dot{q}_p - \dot{q}_c) \cdot \mathbf{n} = \left(k_p \nabla T\Big|_{interface,p} - k_c \nabla T\Big|_{interface,c}\right) \cdot \mathbf{n} = 0 \qquad (3)$$

- **Thermal contact resistance** at the interface

$$T\Big|_{interface,p} - T\Big|_{interface,c} = \frac{\dot{q}_c \cdot \mathbf{n}}{h} \qquad (4)$$

2. Implementation & Verification

Conditional volume averaging technique was used to derive an equation for the mixture temperature T_m [Habla et al., 2013]

- **Thermal contact resistance** at the interface

$$\frac{\partial(\rho_m c_{P,m} T_m)}{\partial t} + \nabla \cdot \left(\mathbf{U}_m \rho_m c_{P,m} T_m\right) - \nabla \cdot k_m \nabla T_m =$$

$$-\nabla \cdot \left[\frac{k_m \nabla \alpha_p - \alpha_p \alpha_c \left(\overline{k}^p - \overline{k}^c\right)\left(\frac{1}{\overline{k}^p} - \frac{1}{\overline{k}^c}\right) h\mathbf{n}}{h\left(\frac{\alpha_p}{k^p} + \frac{\alpha_c}{k^c}\right) + \nabla \alpha_p \cdot \mathbf{n}}\right] \nabla T_m \cdot \mathbf{n} \qquad (5)$$

Habla, F., Dietsche, L., Hinrichsen, O., 2013. Modeling and simulation of conditionally volume averaged viscoelastic two-phase fows. AIChE Journal 59 (10), 3914-3927.

2. Implementation & Verification

- **OpenFOAM** code

```
// Temperature equation with jump
tmp<fvScalarMatrix> TEqn
(
    fvm::ddt(rhoCp, T)
  + fvm::div(phi * rhoCpf, T, "div(phi,T)")
  - fvm::laplacian(k, T, "laplacian(k,T)")
  ==
  - fvc::div(sjump)
);
```

where

```
surfaceScalarField sjump
(
    (gradTf & nHatf)*(kf - solidf*(1-solidf)*(ksolid-kpolymer)*(1/ksolid-1/kpolymer)*h/(mag( fvc::snGrad(solid) )+gradStab))
    /((gradSolidf & nHatf) + h*(solidf/ksolid + (1-solidf)/kpolymer))
     * fvc::snGrad(solid) * mesh.magSf()
);
```

2. Implementation & Verification

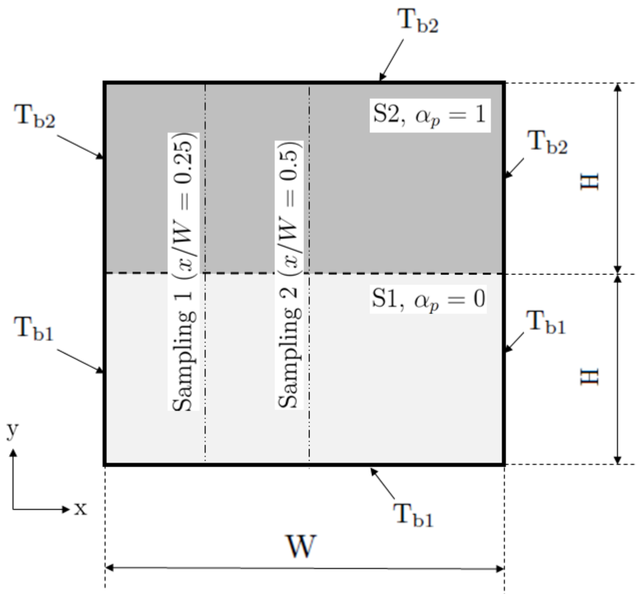
- **Boundary conditions** (radiation & convection)

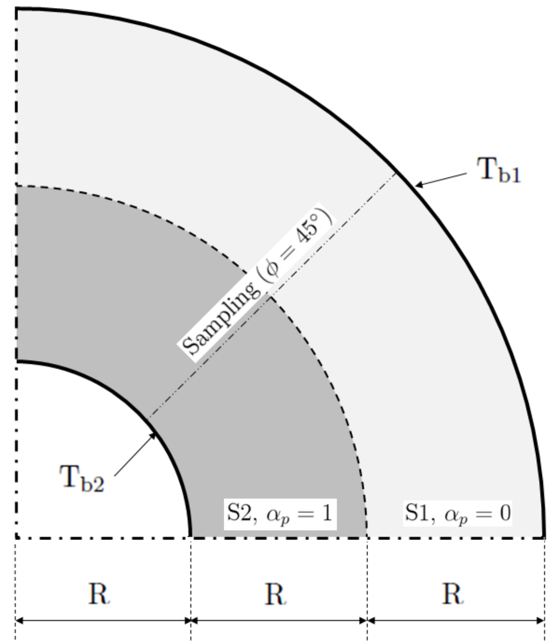
$$\nabla T_{m|b,i} = \frac{\epsilon_i \sigma}{k_i}\left(T_{m|b,i}^4 - T_{m,\infty}^4\right) + \frac{\alpha_i}{k_i}\left(T_{m|b,i} - T_{m,\infty}\right) \tag{6}$$

```
scalarField d = 1/this->patch().deltaCoeffs();

scalarField C1 = epsilon_ * d * 5.6704e-8 / k_;

scalarField C2 = alpha_ * d / k_;

for(int i=0; i<it_; i++)
{
        that = ((pif+273.15) - C1*(pow(that,4) - pow((Tinf_+273.15),4)) + C2*(Tinf_+273.15))/(1+C2);
}
```

2. Implementation & Verification

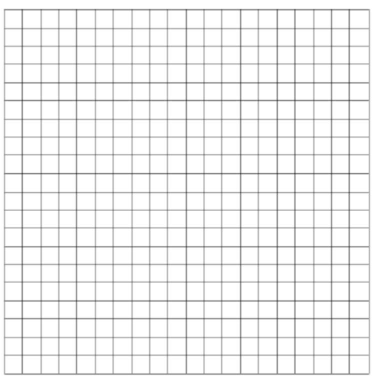
- Method of the Manufactured Solutions (MMS) – code verification (detection of discretization errors)
- Analytical Solutions (two juxtaposed slabs and concentric cylinders)



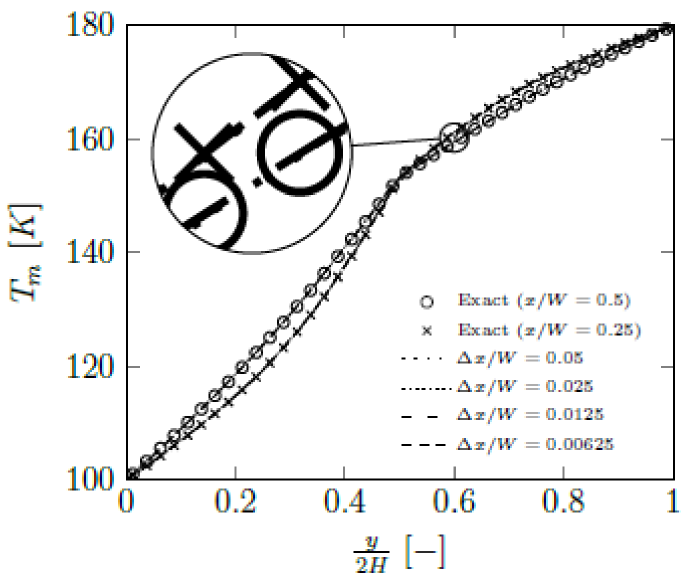


2. Implementation & Verification

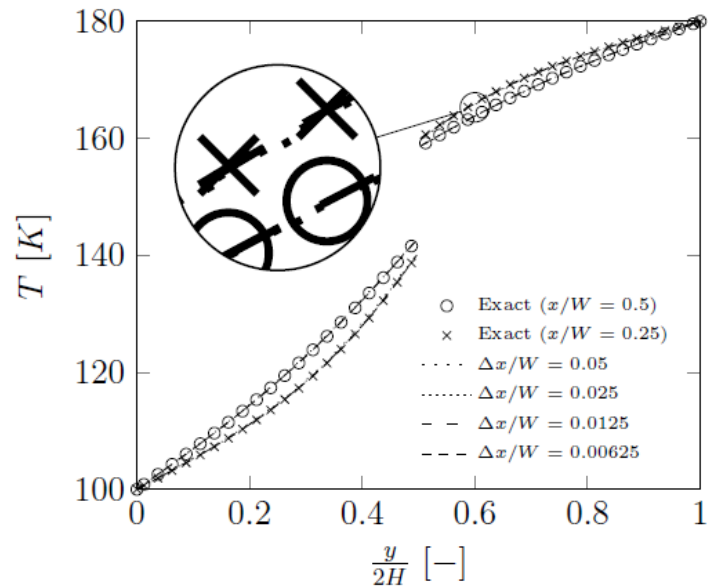
- Analytical Solutions - slab



perfect contact



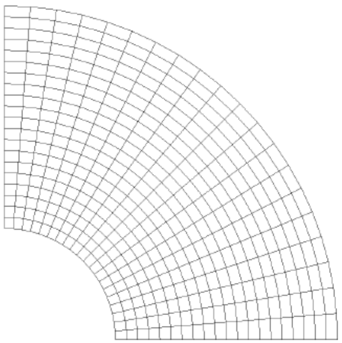
contact resistance

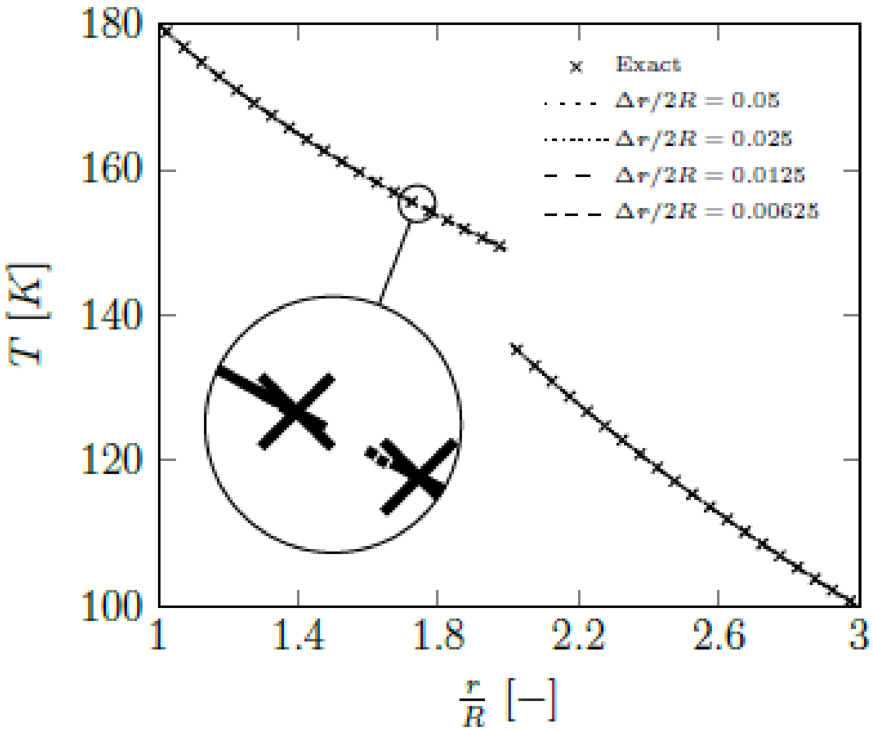


2. Implementation & Verification

- Analytical Solutions – cylinder

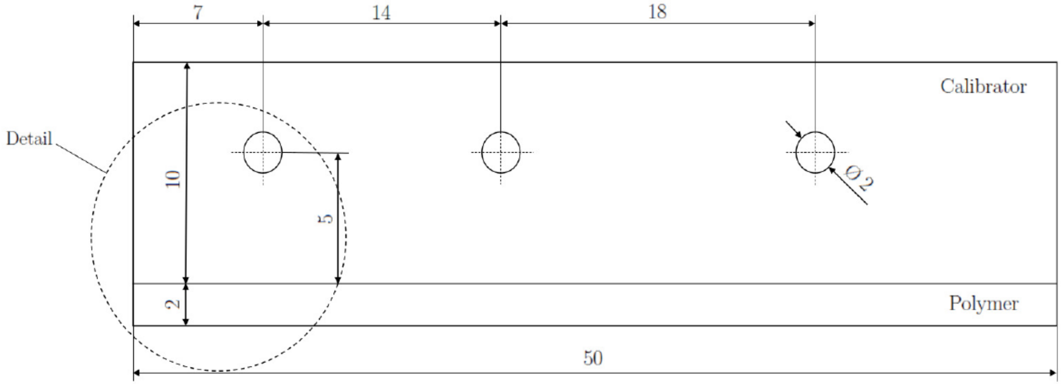
contact resistance

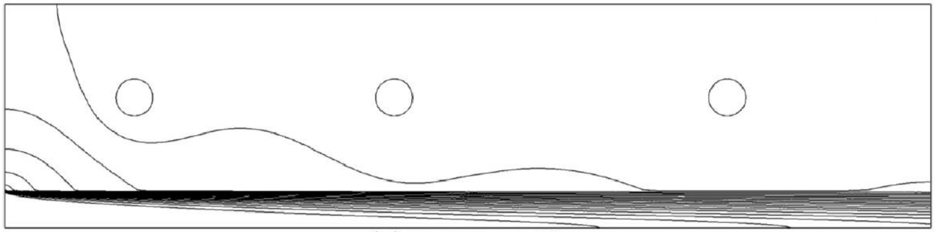




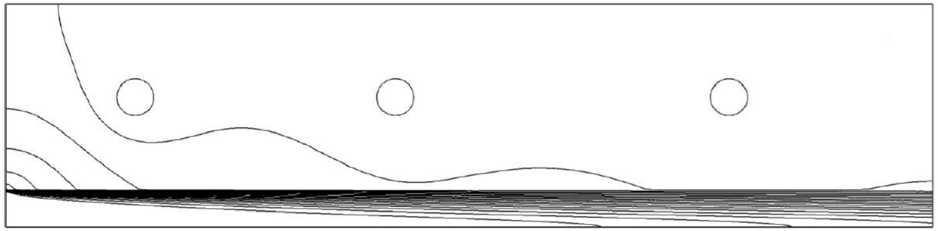
2. Implementation & Verification

- Two dimensional contact test case

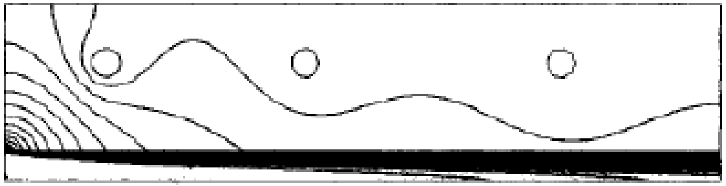




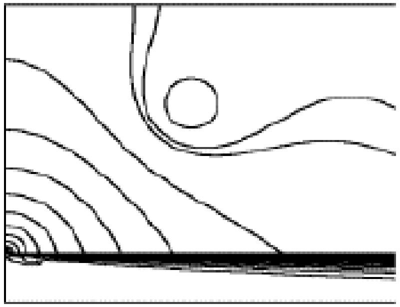
(a) 59,610 cells



(b) 183,050 cells.

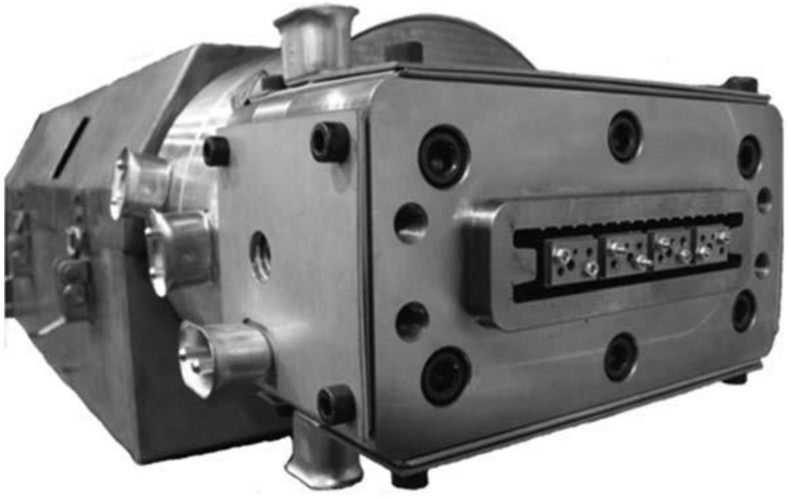


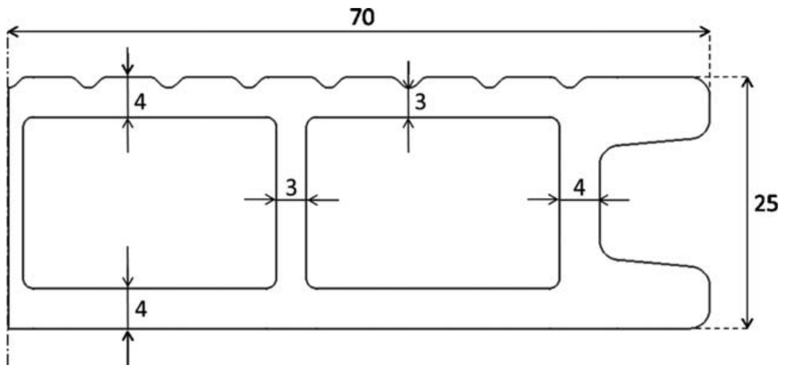
(a) Sheehy et al.

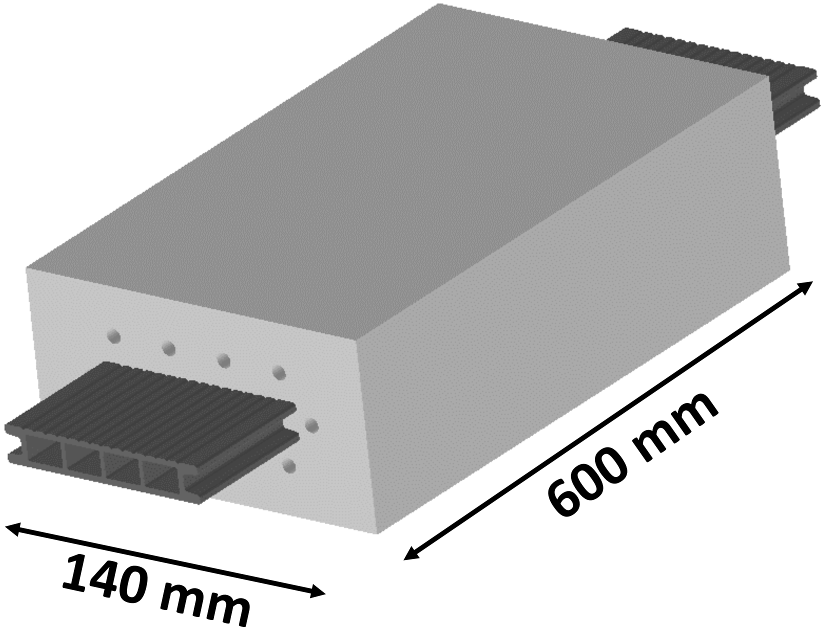


(b) Nóbrega et al.

3. Case study | *modeling* | Geometry

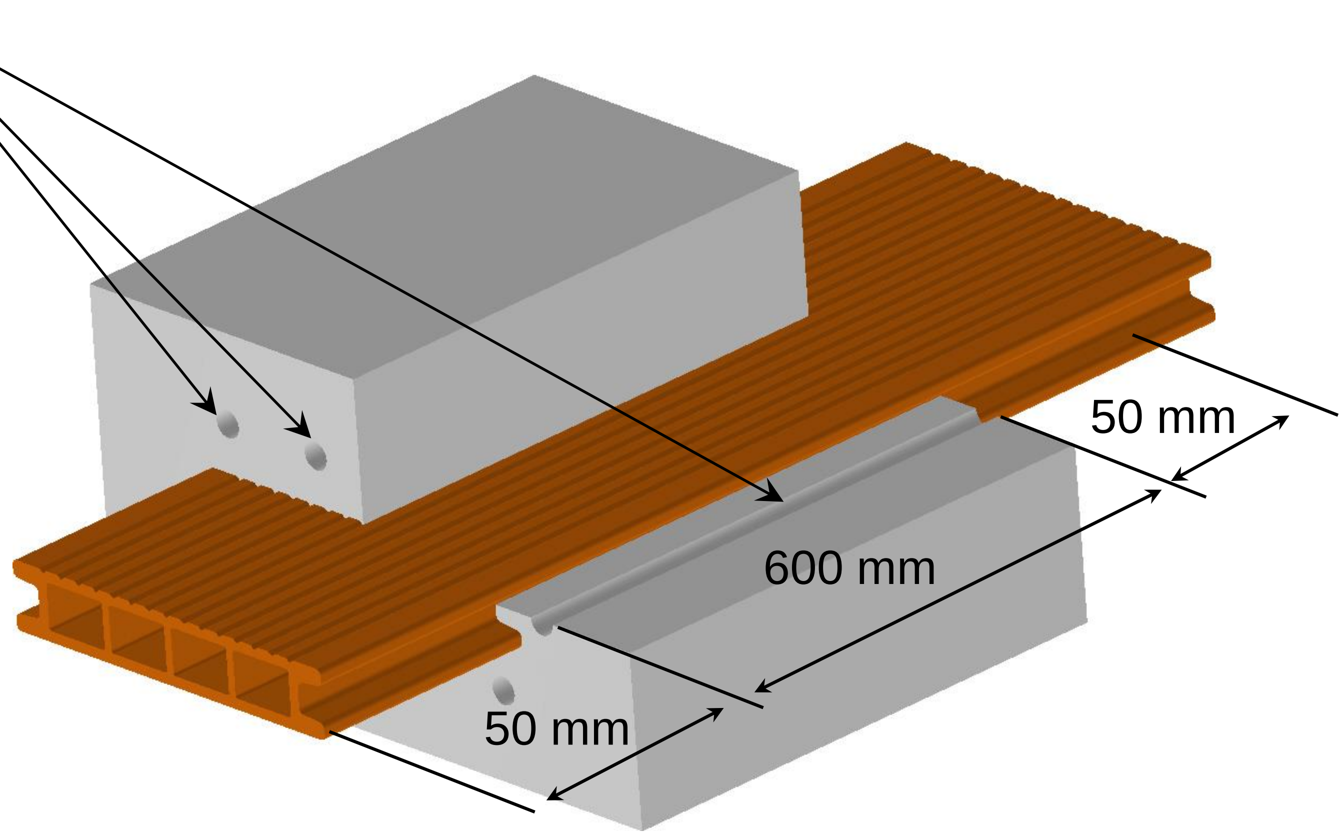






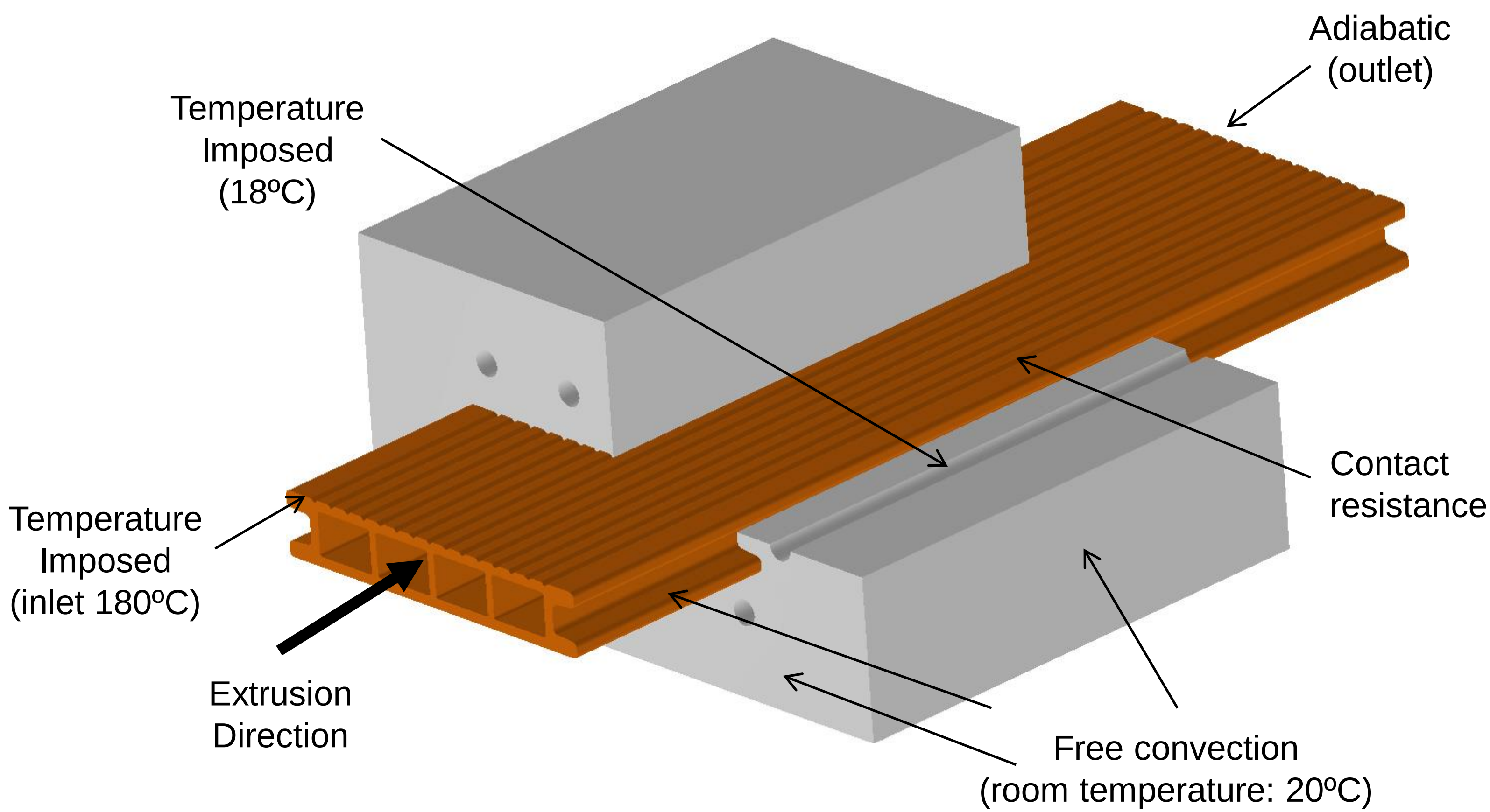
3. Case study | *modeling* | Geometry

10 cooling channels (ø 10 mm)



3. Case study | *modeling* | BC & propert.

- **Thermal BC**
- **Velocity** (0.72 m/min)



3. Case study | *modeling* | BC & propert.

- **Properties**

Metal

- thermal conductivity **(k_c):** 14 W/mK

Polymer

- thermal conductivity **(k_p):** 0.18 W/mK
- density **(ρ_p):** 1400 kg/m^3
- heat capacity **(c_p):** 1000 J/kgK

Contact resistance at the interface (h): 500 W/m^{2}K

Heat transfer coeff. – free convection: 5 W/m^{2}K

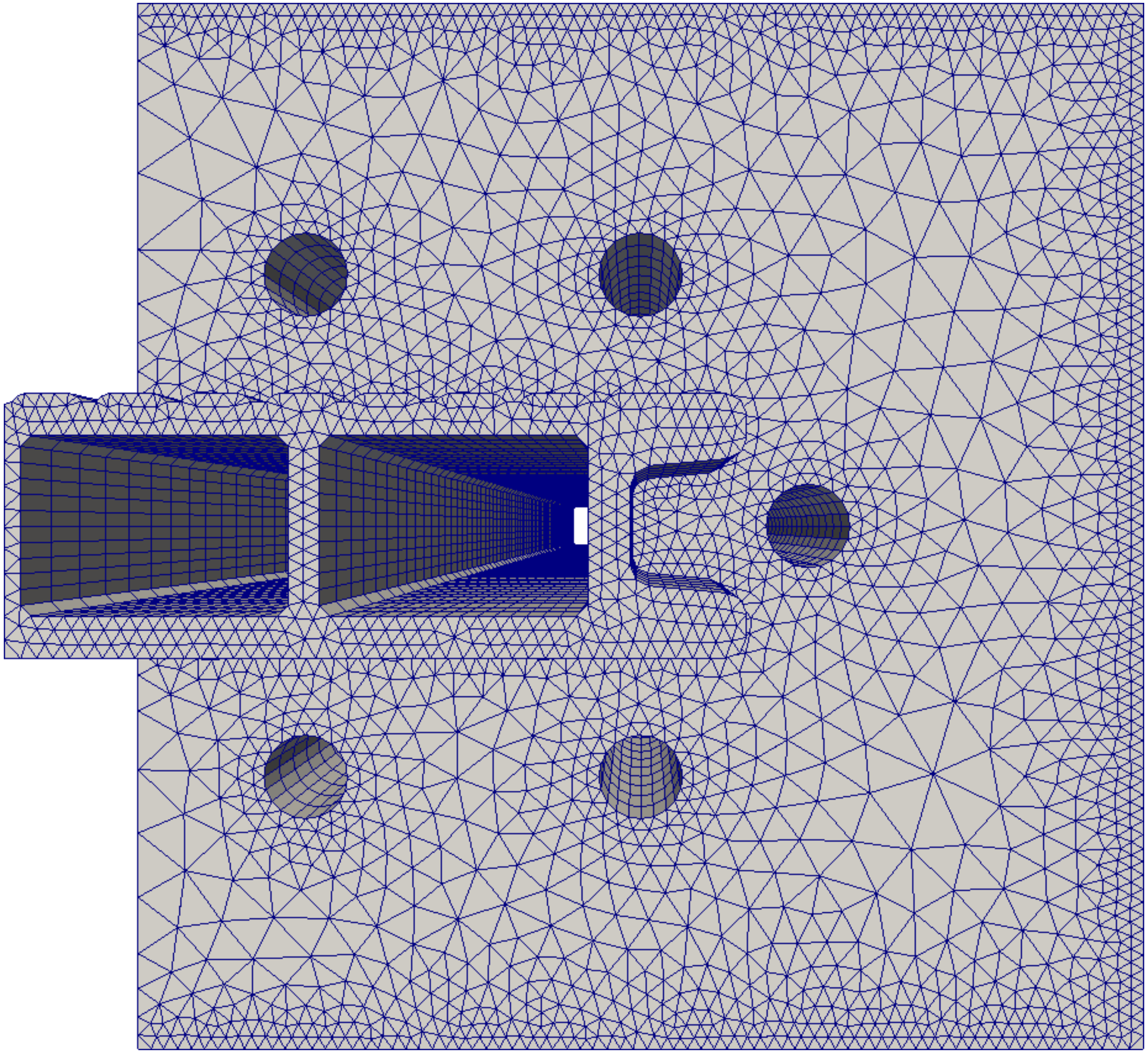
3. Case study | *modeling* | Mesh study

M1

Parameter for **length divisions: 0.010 m**
Cell maximum size: 0.032
Cell minimum size: 0.0024

Edges refinement: 0.0016
(in all edges except in symmetry)

Number of cells:
286 770



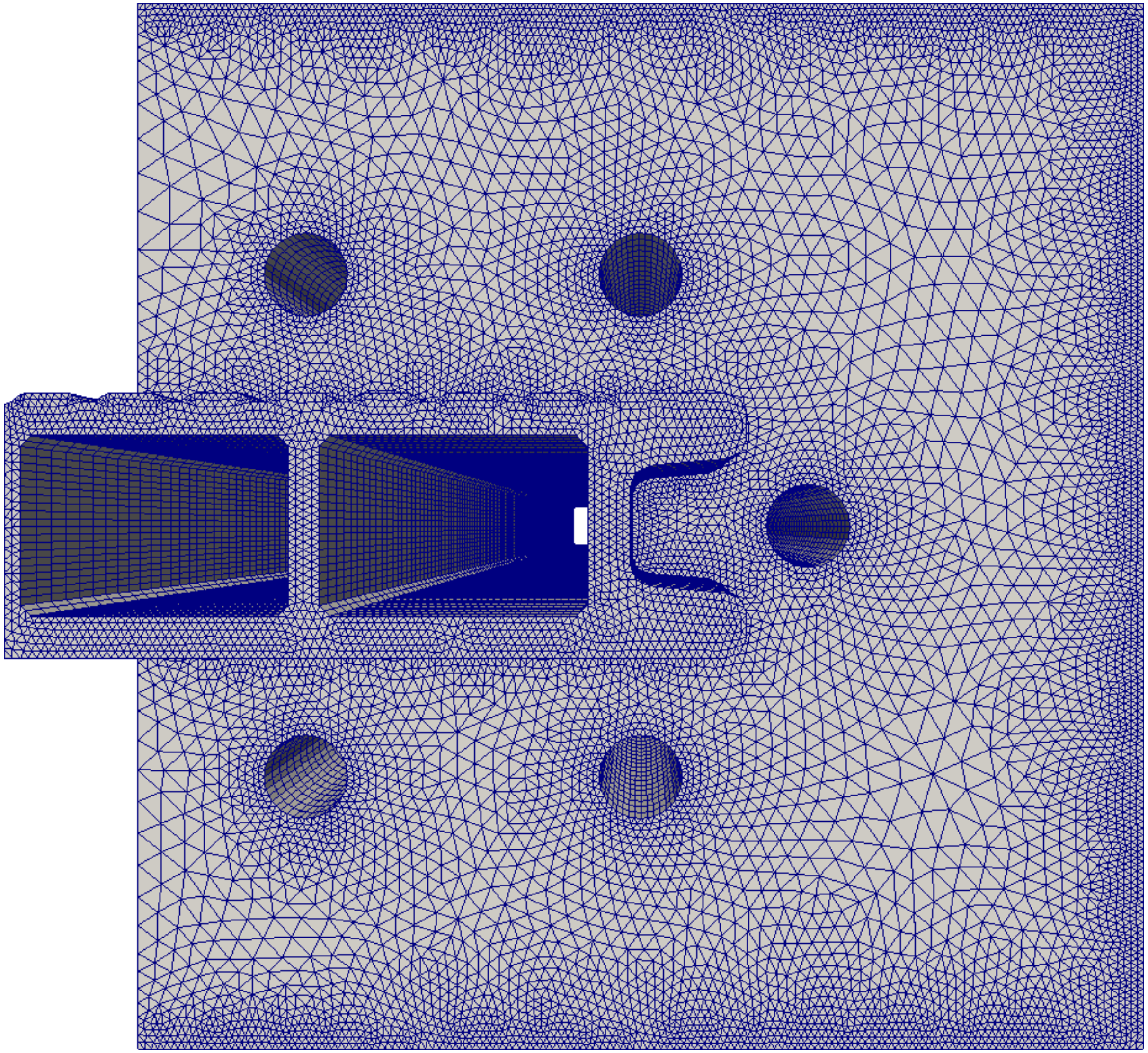
3. Case study | *modeling* | Mesh study

M2

Parameter for **length divisions: 0.005 m**
Cell maximum size: 0.016
Cell minimum size: 0.0012

Edges refinement: 0.0008
(in all edges except in symmetry)

Number of cells:
2 294 160



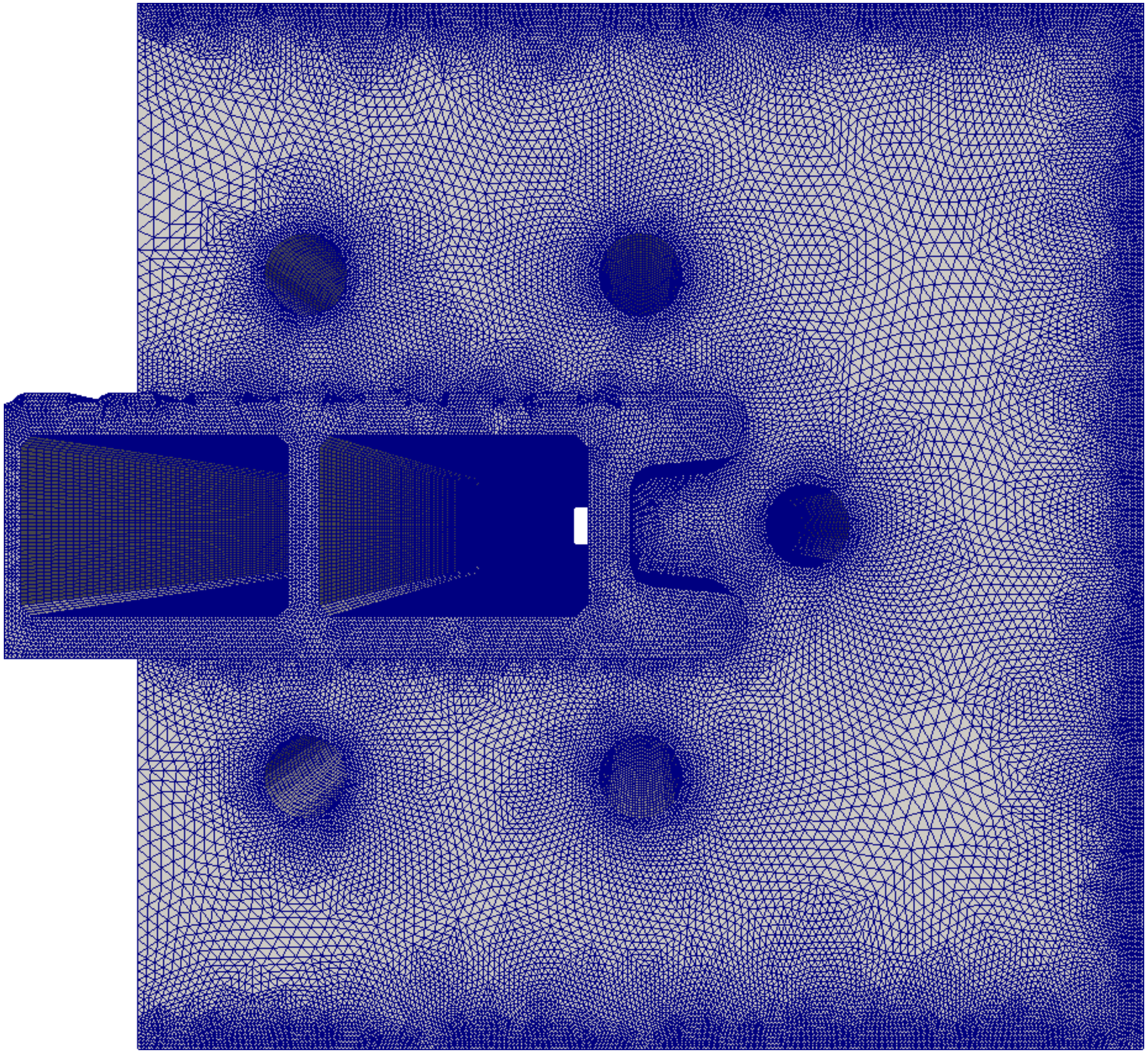
3. Case study | *modeling* | Mesh study

M3

Parameter for **length divisions: 0.0025 m**
Cell maximum size: 0.008
Cell minimum size: 0.0006

Edges refinement: 0.0004
(in all edges except in symmetry)

Number of cells:
18 353 280



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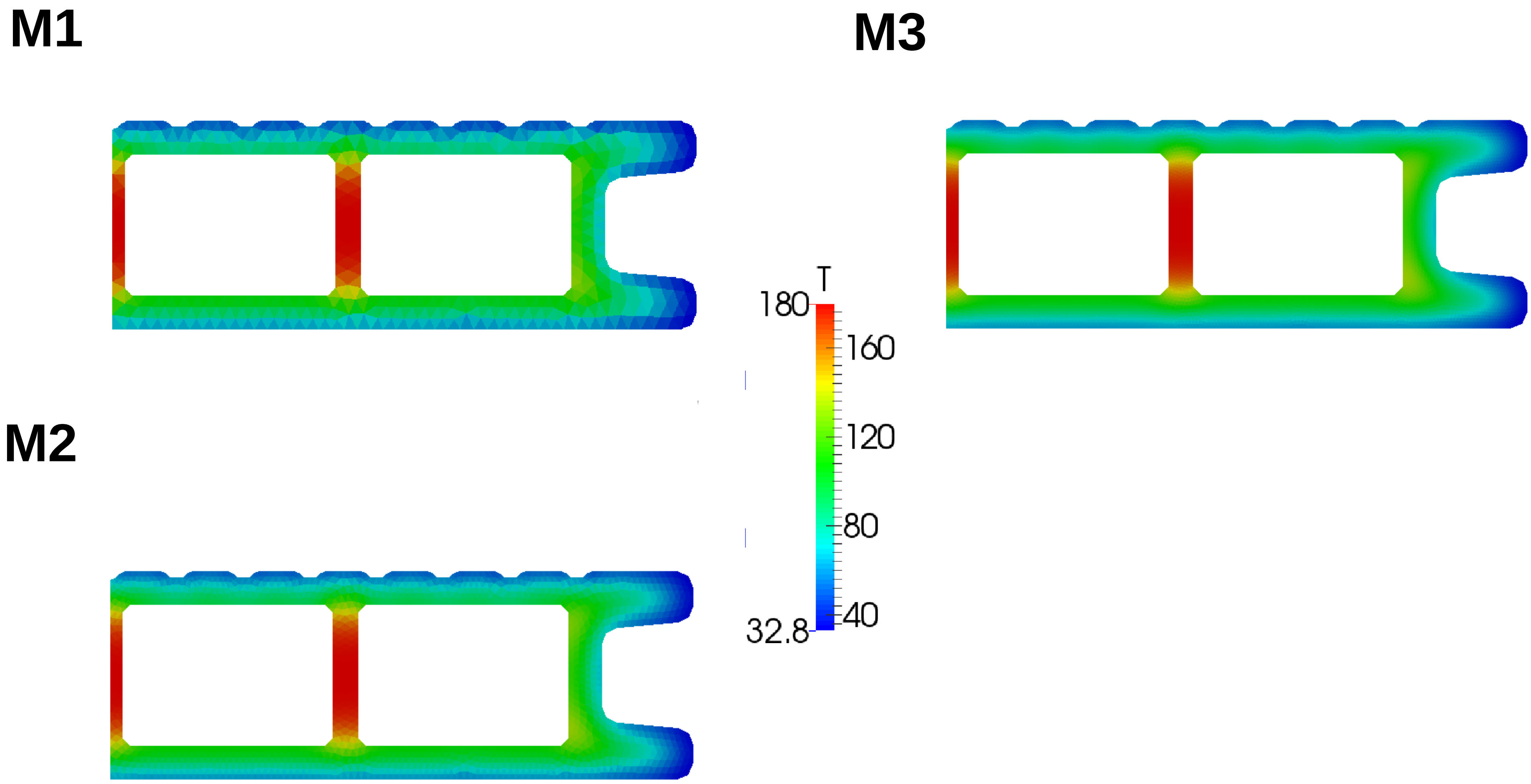


3. Case study | *modeling* | Mesh study

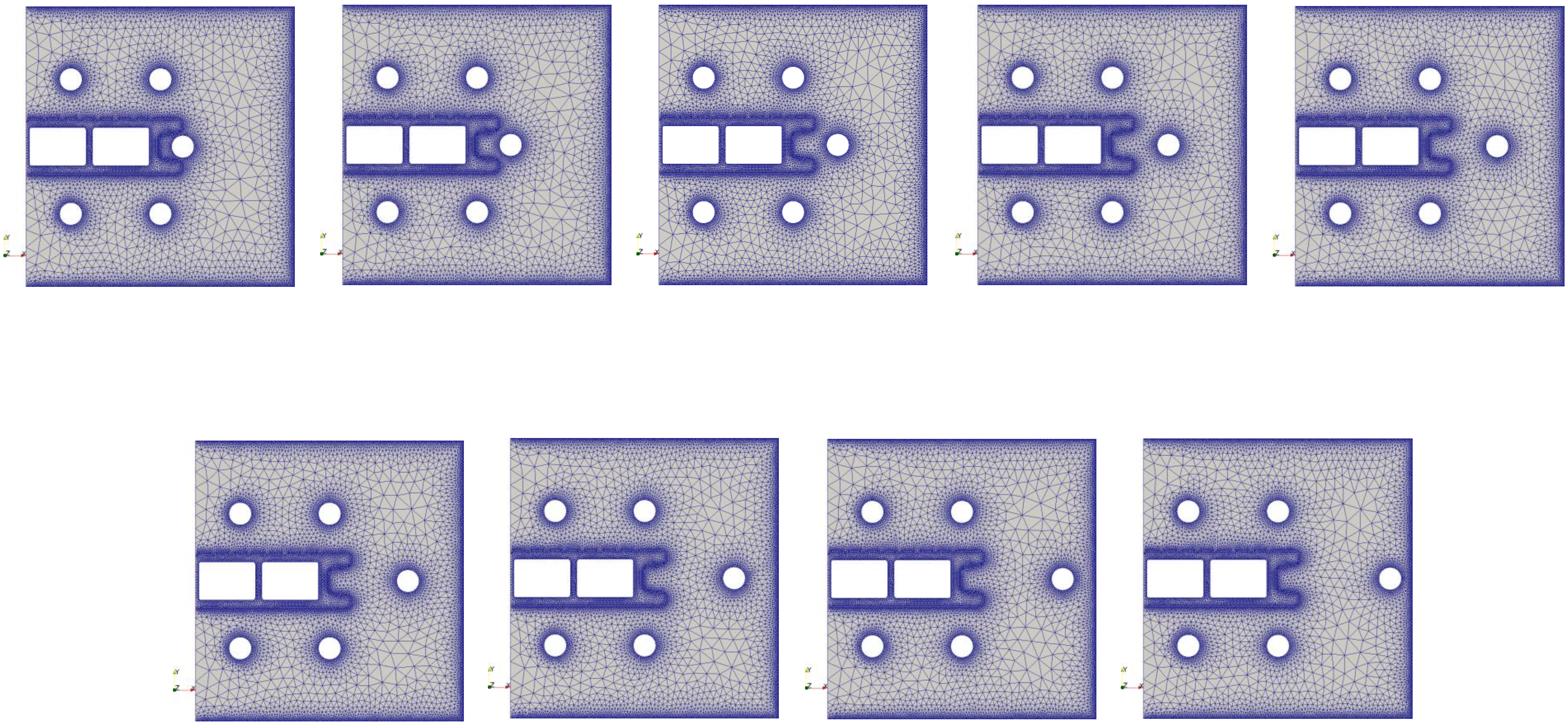
Mesh	Average temperature (ºC)	Temperature standard deviation (ºC)	Simulation time (s)
M1	86.2581	34.4908	7
M2	88.8541	33.9741	96
M3	90.2010	33.8008	1521

Mesh	Average temperature difference (%)	Temperature standard deviation difference (%)
M1-M2	3.01	1.50
M2-M3	1.52	0.51

M2 was selected to proceed with this study

4. Case study | *optimization* |One channel

Parametric study of right cooling channel location



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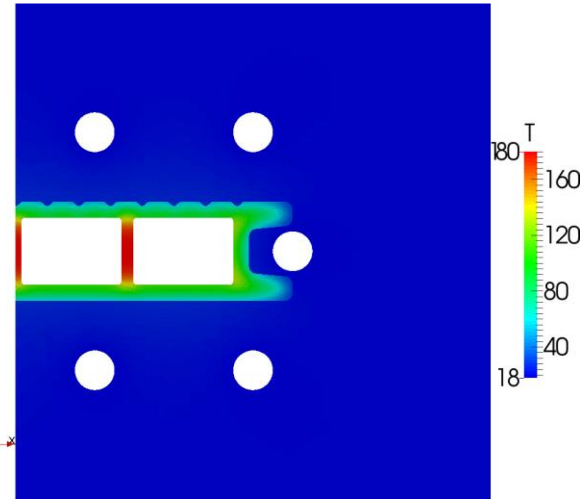
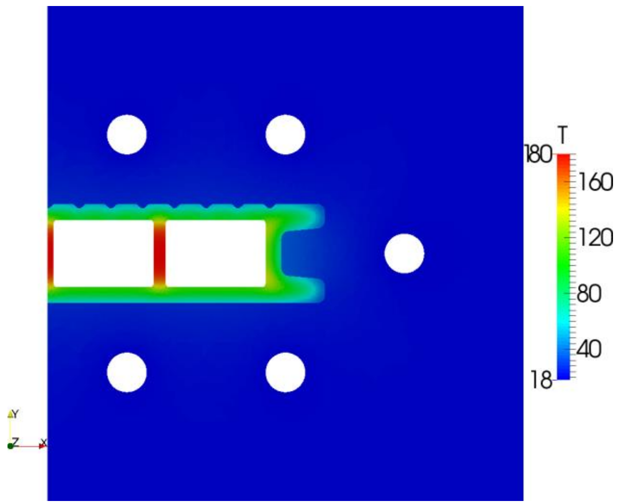
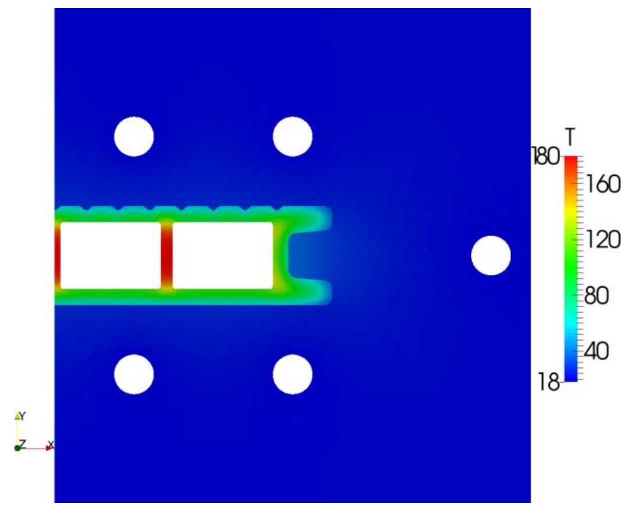


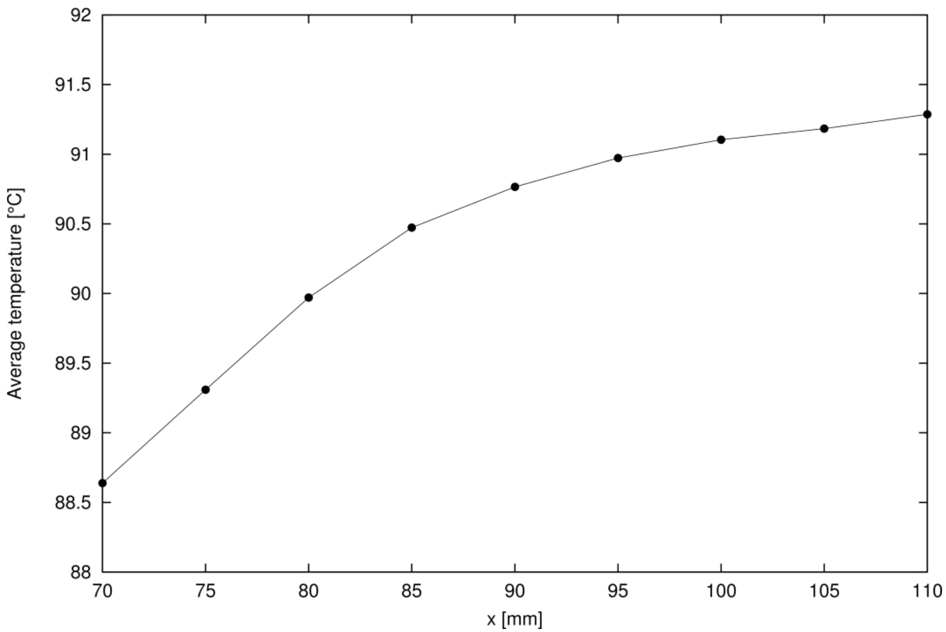




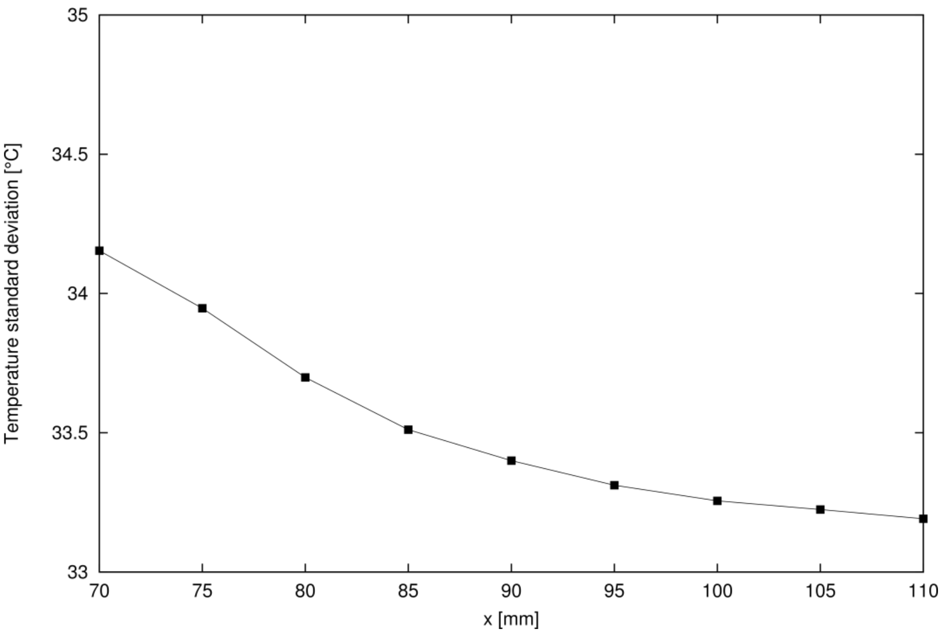
4. Case study | *optimization* |One channel

Parametric study of right cooling channel location

Average T

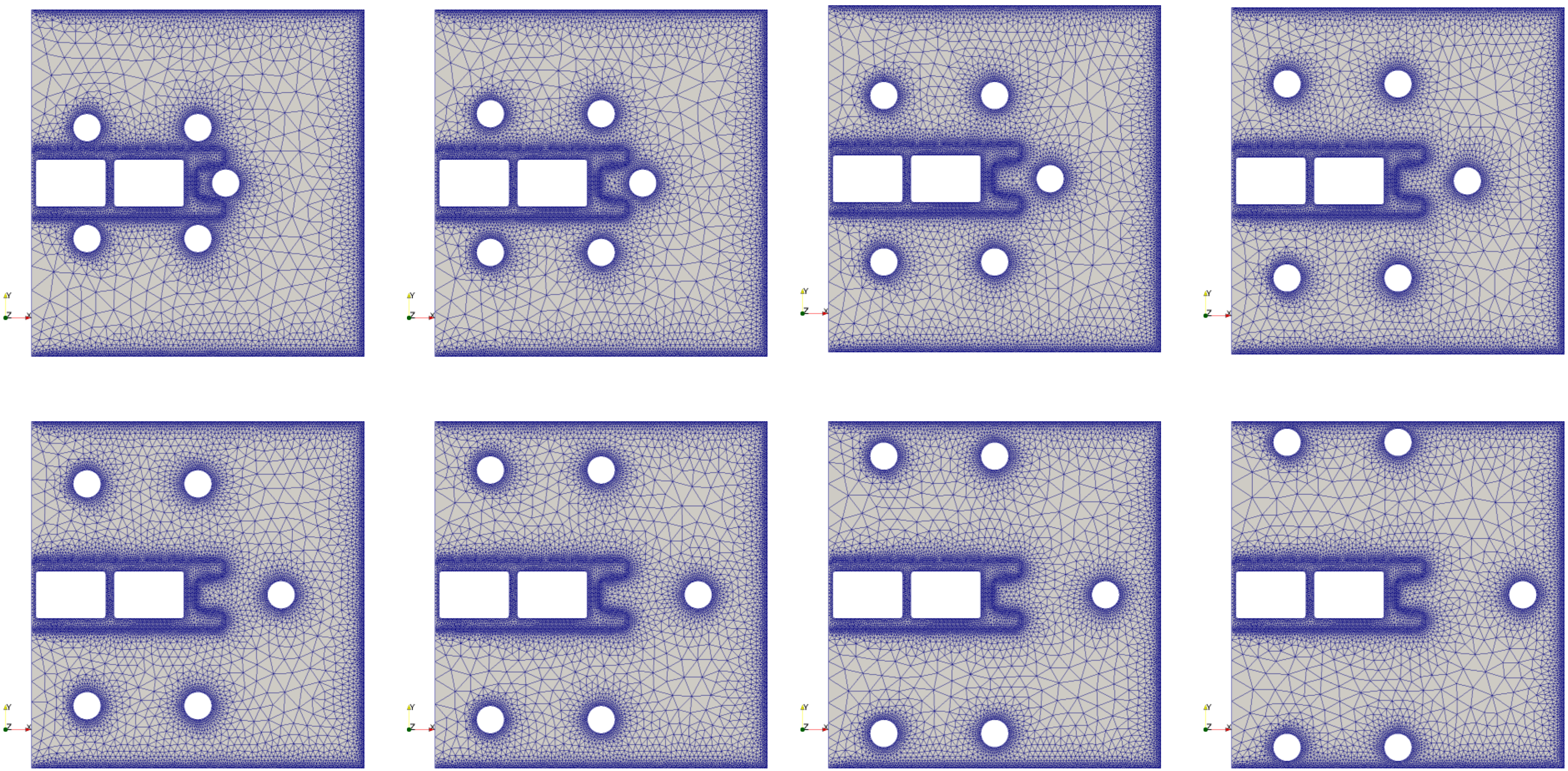


T standard deviation



4. Case study | *optimization* |All channels

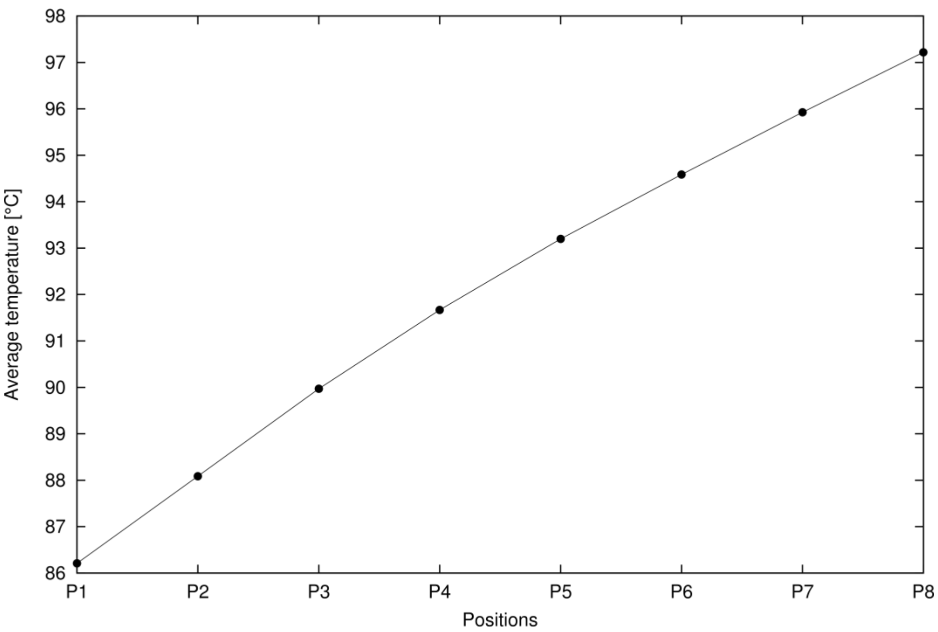
Parametric study of all cooling channels location



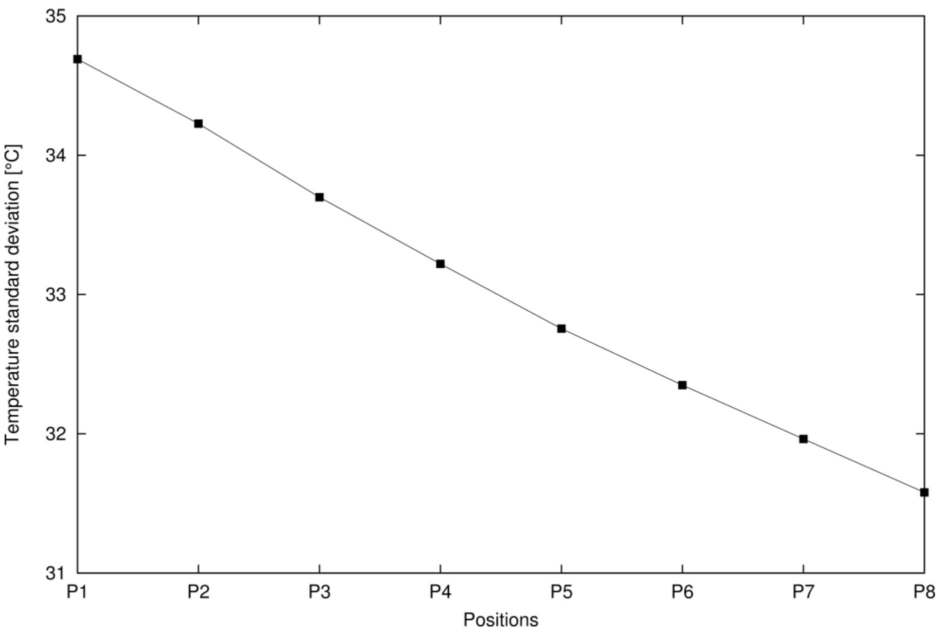
4. Case study | *optimization* |All channels

Parametric study of all cooling channels location

Average T

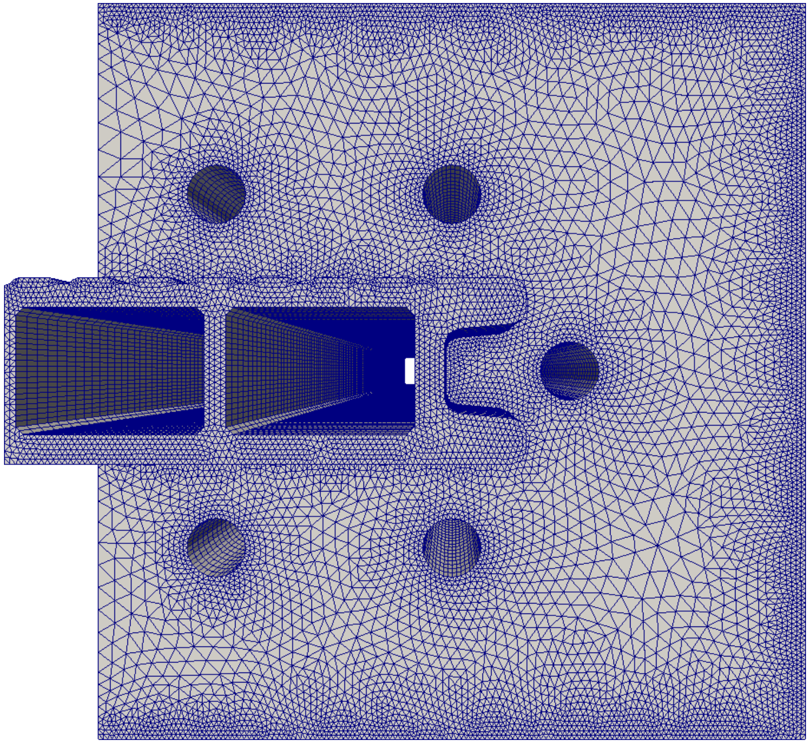


T standard deviation



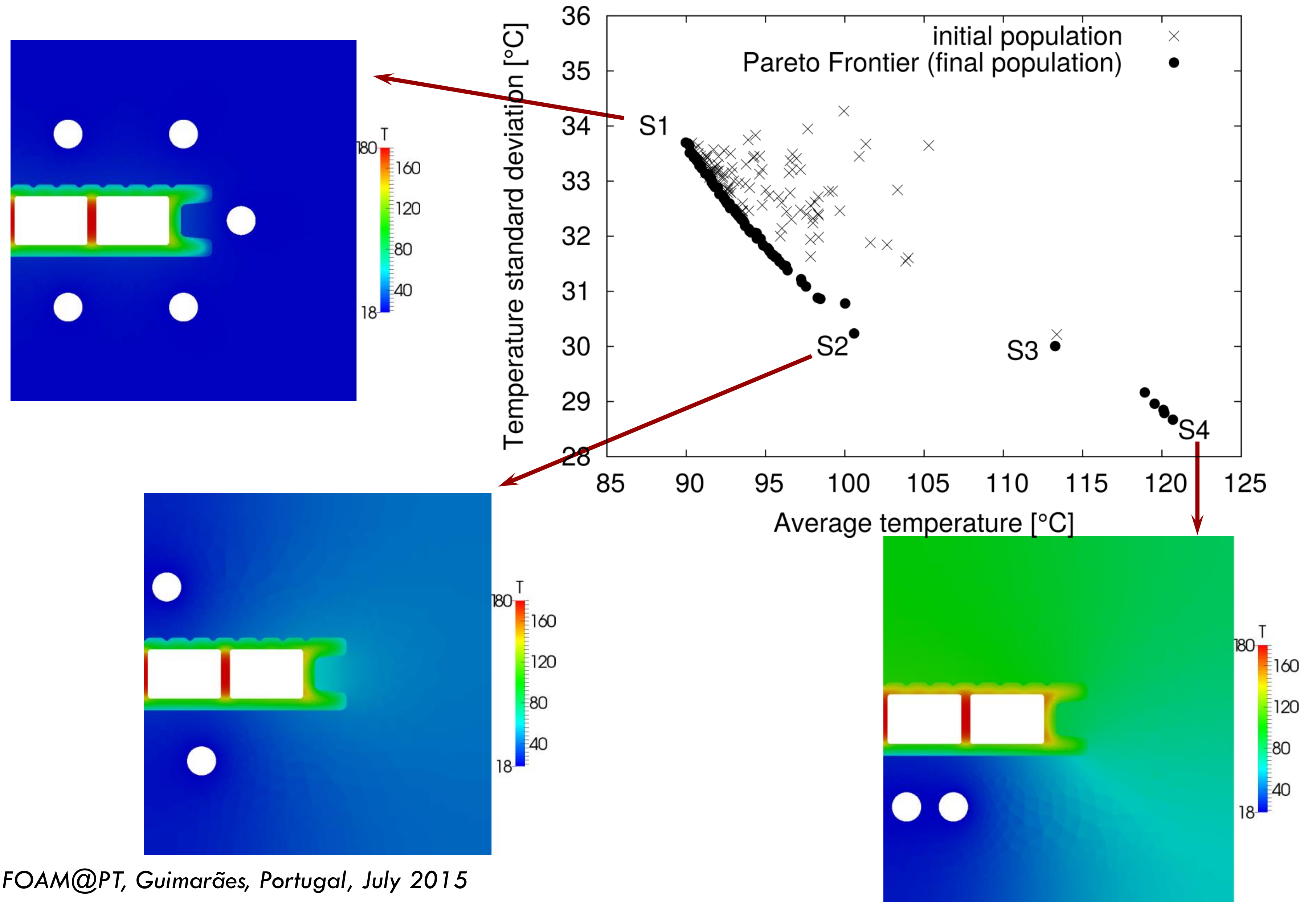
4. Case study | *optimization* |Multi-objective

- Multi-objective Evolutionary Algorithm
- 100 individuals population
- 10 generations



- Maximum no. of channels – 5
- Centre of the cooling channels at a fixed distance to the profile surface (5 mm)
- Overlap channels whenever their centres' distance in less than D+2 mm

4. Case study | *optimization* |Multi-objective



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5. Conclusions

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- The solver is capable to compute the temperature distribution in a two domain system (polymer & calibrator) and to account for a discontinuity at the interface
- The computational time required for performing one simulation showed to be adequate for optimization purposes
- A multi-objective optimization of the cooling channels layout was performed for a realistic case study, resulting in final acceptable solutions

Thank you for your attention!