Flow and heat transfer through an open-cell metal foam

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Presentation overview

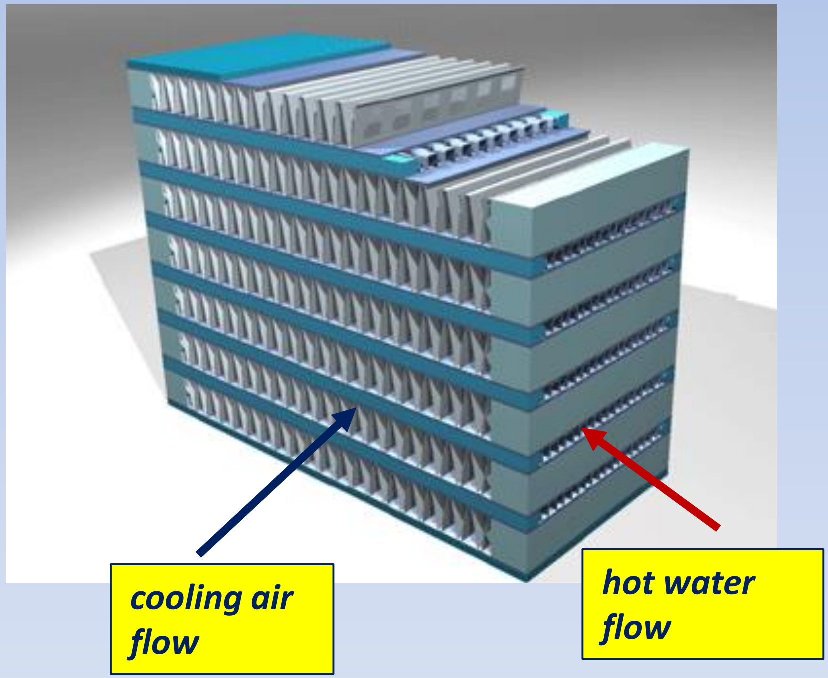
- Open-cell metal foam, heat exchanger
- Physical model and governing equations
- Numerical results
- Conclusions

Open-cell metal foam, compact heat exchanger

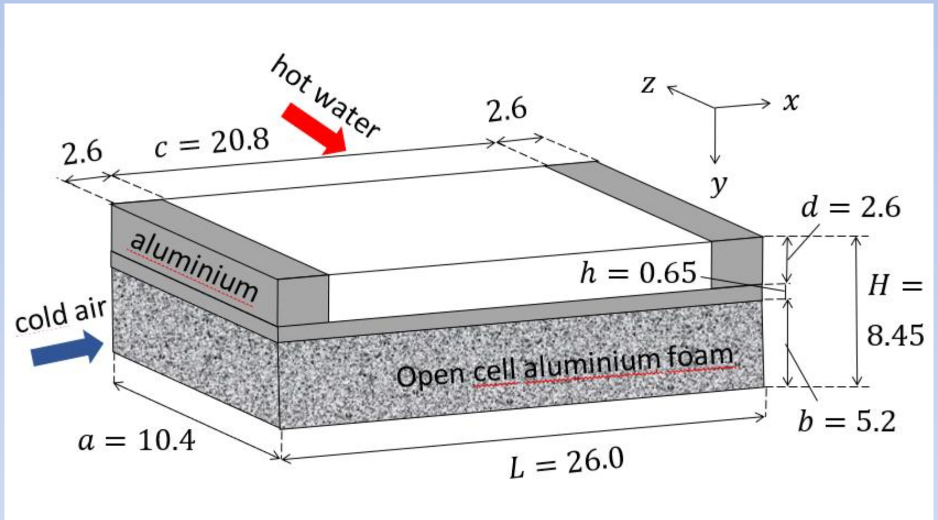
- Open-cell metal foams (or metal sponge) can be used to enhance heat transfer in many applications, such as cryogenic heat exchanger, **compact heat sinks and heat exchanger.**

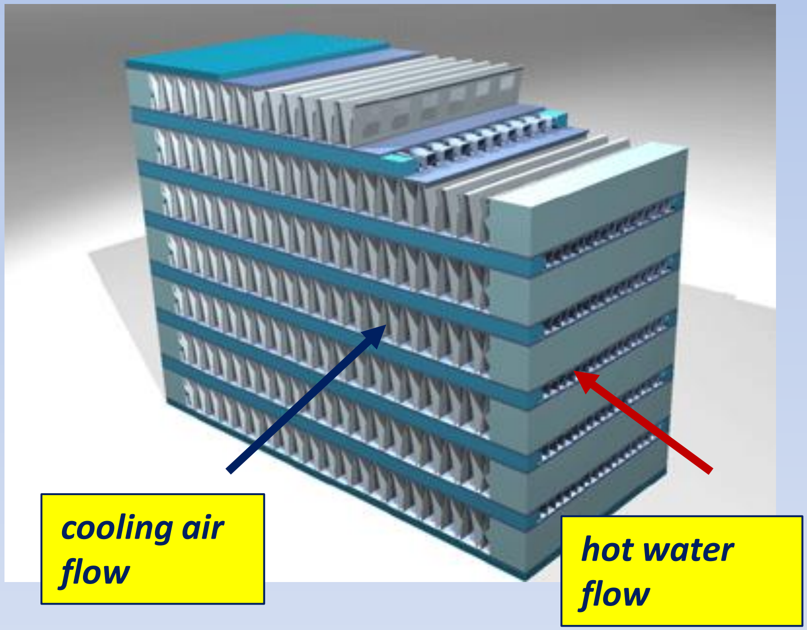
- They are characterized by a **cellular structure** represented by a metal (or a metal alloy) and connected gas voids inside.

- Due to their intrinsic **high porosity and large specific surface area,** these materials are considered to have very promising properties to improve efficiency and minimize the required weight and volume of **novel industrial heat exchangers.**



Physical model: geometry of the heat exchanger section





dimensions are given in mm

Physical model: open-cell metal foam

Aluminium sponge 1	
Length l of the unit cube edge	2.60 mm
Radius R of the inner cylinders	1.20 mm
Length l of the inner cylinders	2.60 mm
Minimum thickness eh of the cell strut	0.10 mm
Minimum thickness 2eh of a strut between two consecutive cells	0.20 mm
Pore density	**~ 10 pores per linear inch**
Volume of the pores V_p	1.25721×10^{-6} m^3
Volume of the solid struts V_s	1.4889×10^{-7} m^3
Porosity $\varepsilon = V_p / V_s$	**89.41%**
Surface area of the struts S_s	8.13×10^{-4} m^2
Total volume of the aluminium sponge V_f	1.4061×10^{-6} m^3
Specific surface area of the aluminium sponge S_s / V_f	**578 m^2/ m^3**

Aluminium sponge 2	
Length l of the unit cube edge	2.60 mm
Radius R of the inner cylinders	1.25 mm
Length l of the inner cylinders	2.60 mm
Minimum thickness eh of the cell strut	0.05 mm
Minimum thickness 2eh of a strut between two consecutive cells	0.1 mm
Pore density	**~ 10 pores per linear inch**
Volume of the pores V_p	1.29379×10^{-6} m^3
Volume of the solid struts V_s	1.1231×10^{-7} m^3
Porosity $\theta = V_p / V_s$	**92.01%**
Surface area of the struts S_s	6.69×10^{-4} m^2
Total volume of the aluminium sponge V_f	1.4061×10^{-6} m^3
Specific surface area of the aluminium sponge S_s / V_f	**476 m^2/ m^3**

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Computational work : governing equations

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

$$\rho (\mathbf{u} \bullet \nabla)\mathbf{u} = \nabla \bullet [-p\mathbf{I} + \eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2\eta}{3}(\nabla \bullet \mathbf{u})\mathbf{I}] + \mathbf{F}$$

$$\rho C_p \mathbf{u} \nabla T = \nabla \bullet (k \nabla T) + Q$$

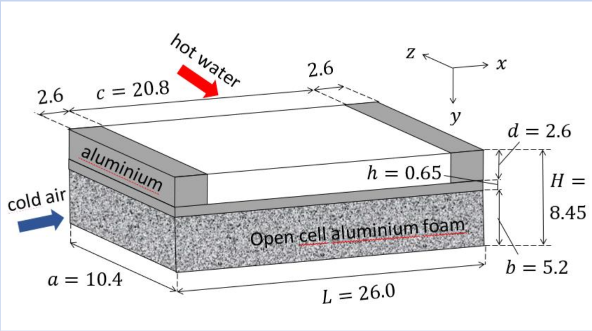
Heat is transferred from a laminar, incompressible stream of hot water to a laminar, compressible flow of cold air by:

- convection and diffusive phenomena in the fluids
- conduction in the solid regions of the system, i.e., walls of device and metal sponge

Steady state compressible fluid flow and heat transfer through the 3D heat exchanger section (Mass and Linear Momentum Conservation; Thermal Energy Conservation)

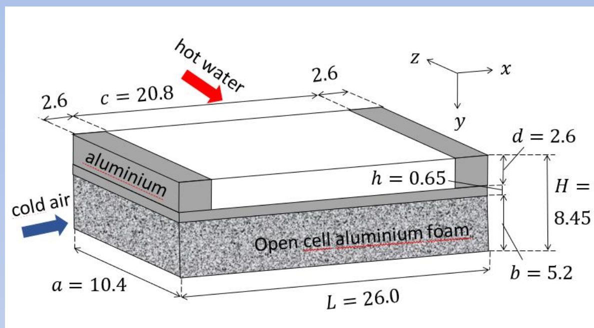
Comsol Multiphysics® 5.4: Heat Transfer and CFD modules

Conjugate Heat Transfer physics interface



dimensions are given in mm

Computational work: hypothesis of the model



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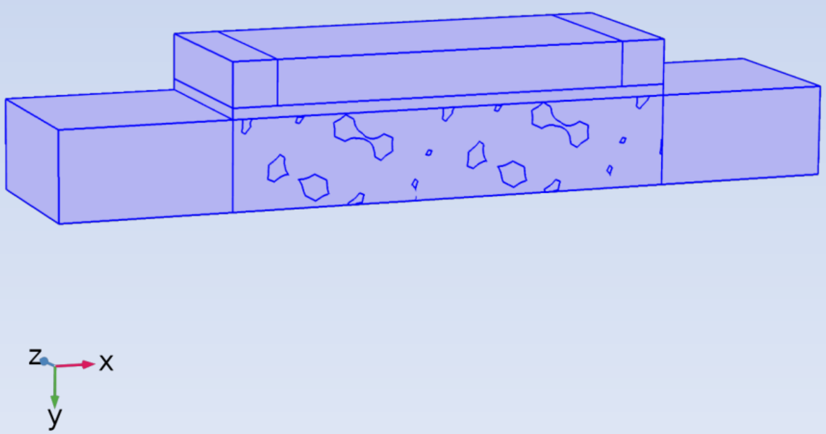
- **Model is 3D**
- **Flow is stationary, laminar, compressible**



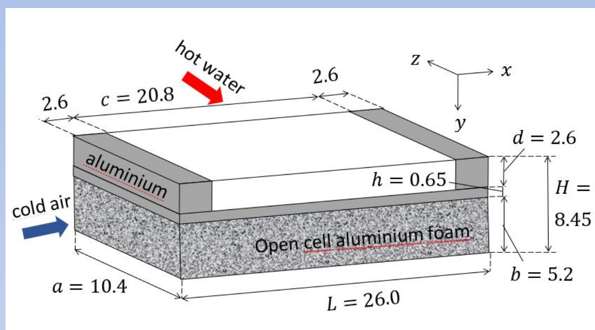
Boundary conditions for the fluid flow:

- at the inlet, a normal velocity *Uin,w* of 0.05 m/s for the water flow and three different values (0.5 m/s, 1 m/s and 1.5 m/s) for the normal velocity *Uin,a* of the cooling air
- at the outlets, a null gauge pressure
- conditions of symmetry on the top of the water channel and the bottom of the air flow
- conditions of open boundary (normal stresses equal to zero) on the side walls of the foam section
- boundary condition of no slip on the rest of the solid surfaces, including the solid walls of the open-cell foam

Boundary conditions for the heat transfer:

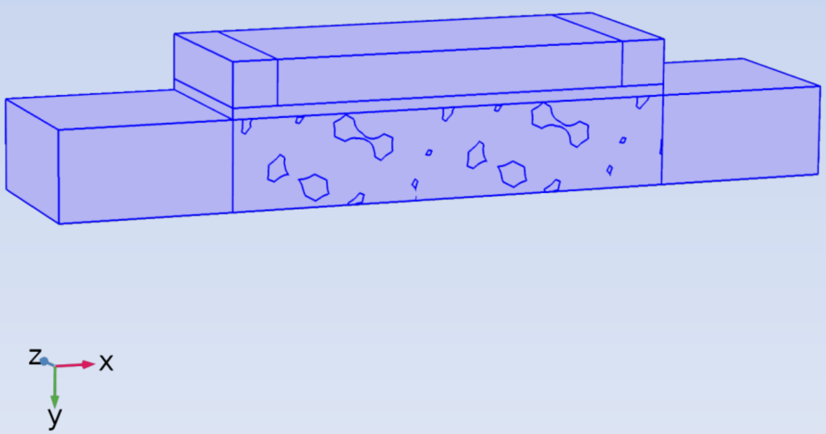
- at the inlets, temperature *Tin,a* of 300 K for the air inflow and temperature *Tin,w* of 330 K for the water inflow
- at the outlets $-\mathbf{n} \bullet \mathbf{q} = 0$ for both fluids (**q** is the heat flux and **n** is the normal direction)
- conditions of symmetry on the bottom of the heat exchanger section
- conditions of thermal insulation on the rest of the surfaces

Computational work: hypothesis of the model



dimensions are given in mm

To preserve the flow structure in the upstream and downstream of the heat exchanger, the computational domain is extended of 20 mm in the x direction (10 mm+10 mm)



Computational work : experimental values

Air inflow at 300 K

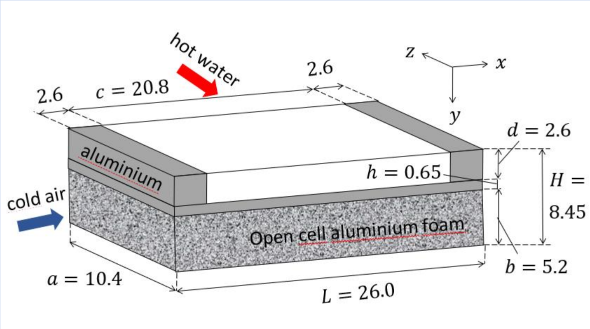
Magnitude	Value
Inlet cross sectional area A_{cs} = (a x b)	5.408×10^{-5} m^2
Wetted perimeter of the flow channel L_p=2 (a + b)	3.120×10^{-2} m
Hydraulic diameter $D_h = 4A_{cs} / L_p$	6.933×10^{-3} m
Temperature at inlet $T_{in,a}$	300 K
Density ρ (at 1atm)	1.1614 kg/m^3
Dynamic viscosity μ (at 1atm)	1.846×10^{-5} Pa·s
Heat capacity at constant pressure c_p (at 1atm)	1.007 kJ/(kg·K)
Prandtl number Pr (at 1atm)	0.707
Inlet velocity $U_{in,a}$	0.5 m/s 1 m/s 1.5 m/s
Mass flow rate $\dot{m} = \rho U_{in,a} A_{cs}$	3.140×10^{-5} kg/s 6.281×10^{-5} kg/s 9.421×10^{-5} kg/s
Reynolds number $Re_h = \rho\, U_{in,w}\, D_h / \mu$	218 436 654
Hydrodynamic entry length $x_{fd,h} \approx 0.05\, Re_h\, D_h$	75.6 mm 151.2 mm 226.8 mm
Thermal entry length $x_{fd,t} \approx 0.05\, Re_h\, D_h\, Pr$	53.5 mm 106.9 mm 160.3 mm

Water inflow at 330 K

Magnitude	Value
Inlet cross sectional area A_{cs} = (c x d)	5.408×10^{-5} m^2
Wetted perimeter of the flow channel L_p=2 (c + d)	4.680×10^{-2} m
Hydraulic diameter $D_h = 4A_{cs} / L_p$	4.622×10^{-3} m
Temperature at inlet $T_{in,w}$	330 K
Density ρ (at p_{sat})	984 kg/m^3
Dynamic viscosity μ (at p_{sat})	0.489×10^{-3} Pa·s
Heat capacity at constant pressure c_p (at p_{sat})	4.184 kJ/(kg·K)
Prandtl number Pr (at p_{sat})	3.15
Inlet velocity $U_{in,w}$	0.05 m/s
Mass flow rate $\dot{m} = \rho U_{in,w} A_{cs}$	0.266×10^{-2} kg/s
Reynolds number $Re_h = \rho U_{in,w} D_h / \mu$	465
Hydrodynamic entry length $x_{fd,h} \approx 0.05\, Re_h\, D_h$	107.5 mm
Thermal entry length $x_{fd,t} \approx 0.05\, Re_h\, D_h\, Pr$	338.5 mm

Solid walls of device and metal sponge:

aluminium alloy Al 6063-T83



dimensions are given in mm

Solution with Comsol Multiphysics 5.4

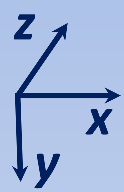
- free tetrahedral volumes, *fine*
- boundary layers on the solid walls, using default values of the software

Parameter	Size
maximum element size	4.97×10^{-4} mm
minimum element size	9.37×10^{-5} mm

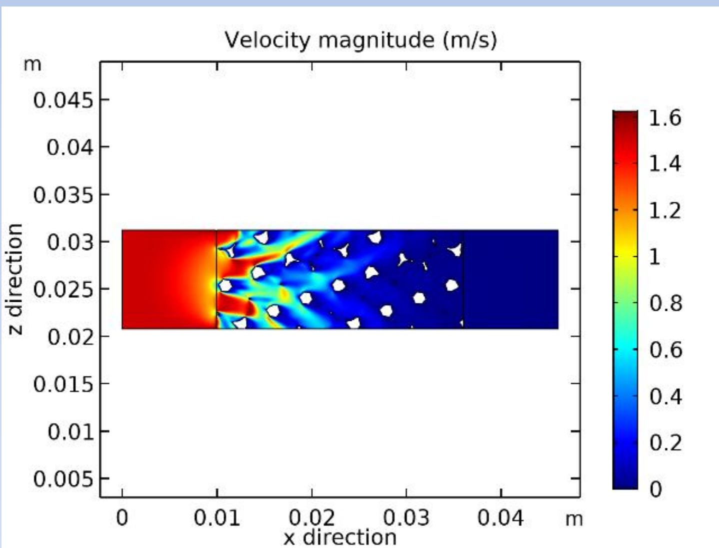
the number of degrees of freedom is approximately 8.5×10^{6}
plus
5×10^{5} internal DOFs

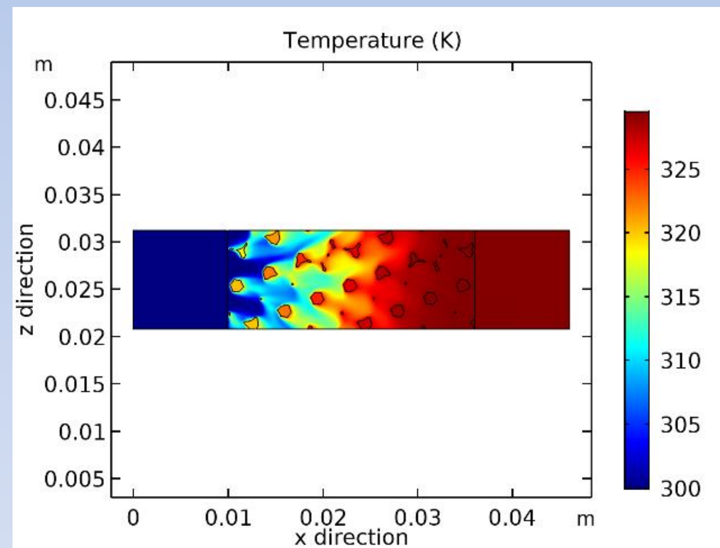
In the following, the computational results are displayed for the aluminium sponge 2 with (porosity of 92.01%) and setting, at the air cooling inlet, a velocity $U_{in,a}$ of 1.5 m/s.

Numerical results: velocity and temperature on a longitudinal plane



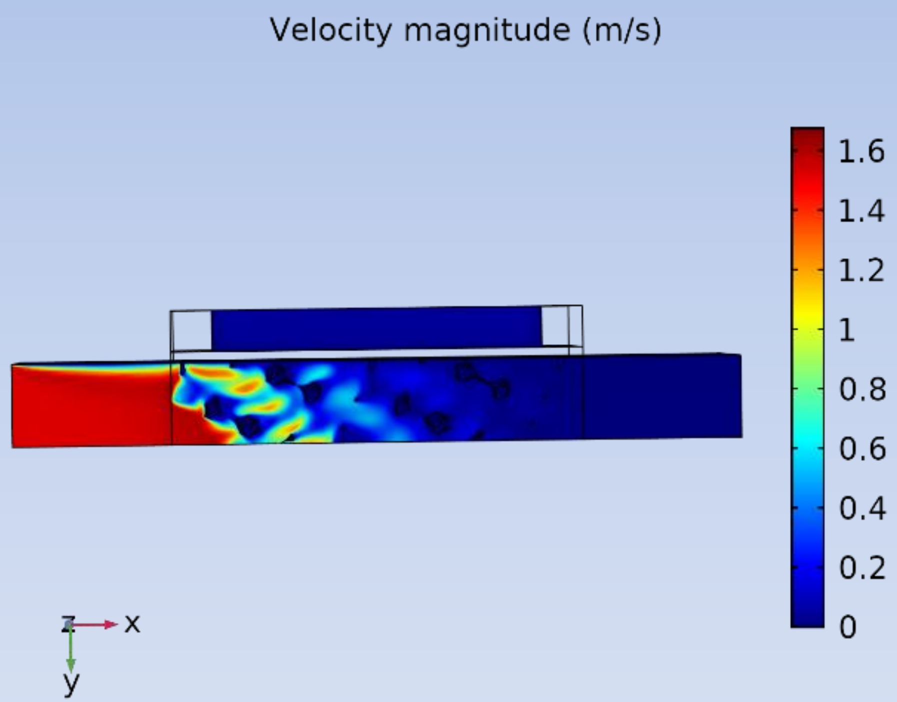
xz surface placed in the middle of the heat exchanger section

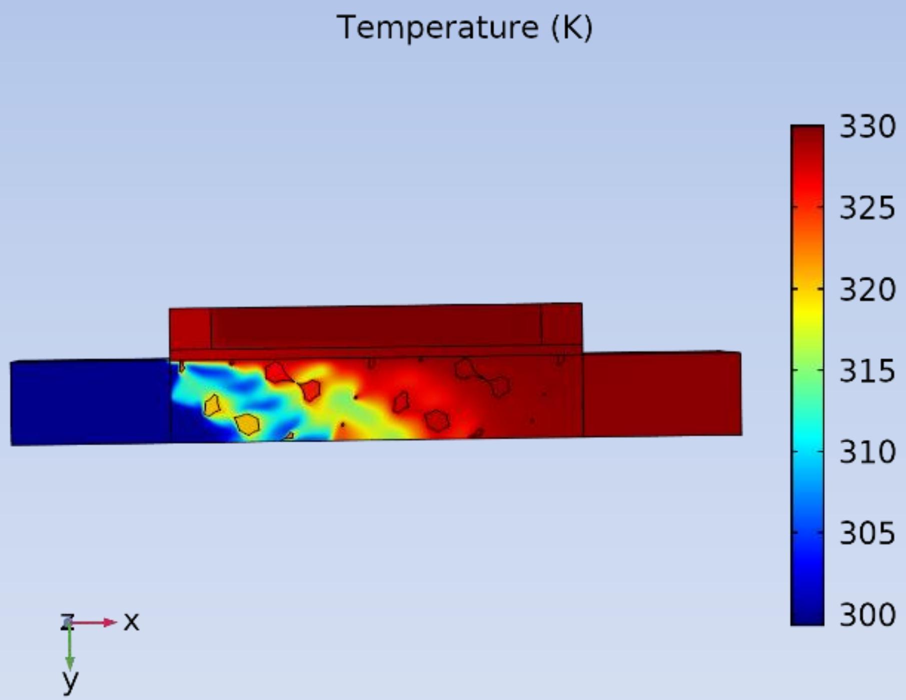




$U_{in,a}$ = 1.5 m/s, $U_{in,w}$ = 0.05 m/s, $T_{in,a}$ = 300 K, $T_{in,w}$ = 330 K , ϑ = 92.01%.

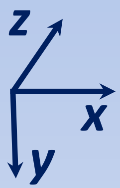
Numerical results: velocity and temperature on a vertical plane

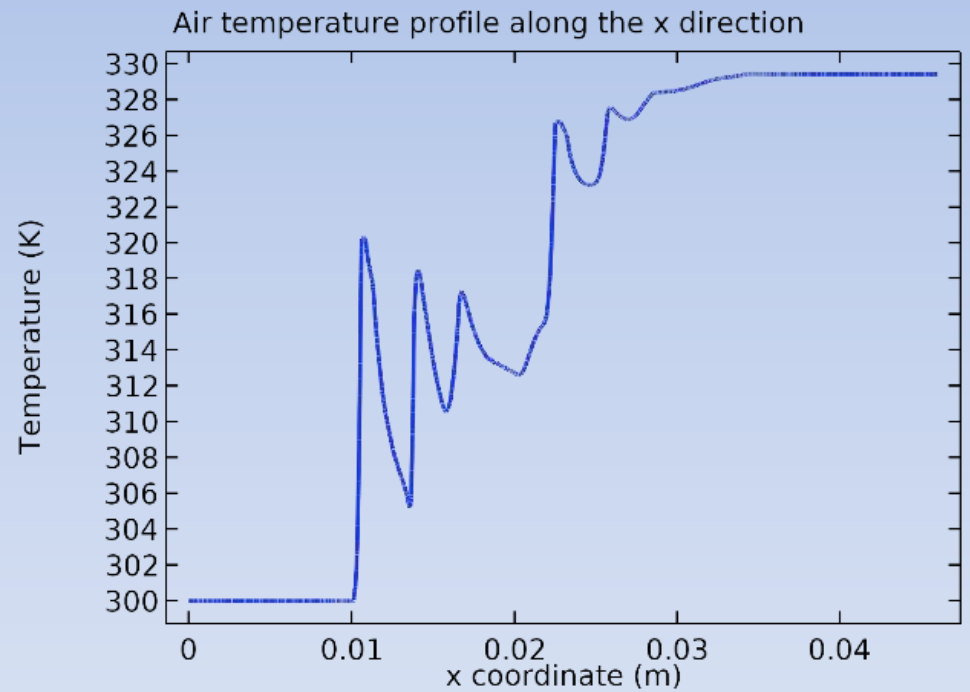




Numerical results: temperature profile in the direction of air flow

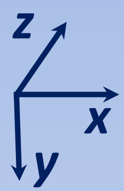
on the intersection of the two central *xz* and *xy* planes
(surfaces placed in the middle of the heat exchanger section)





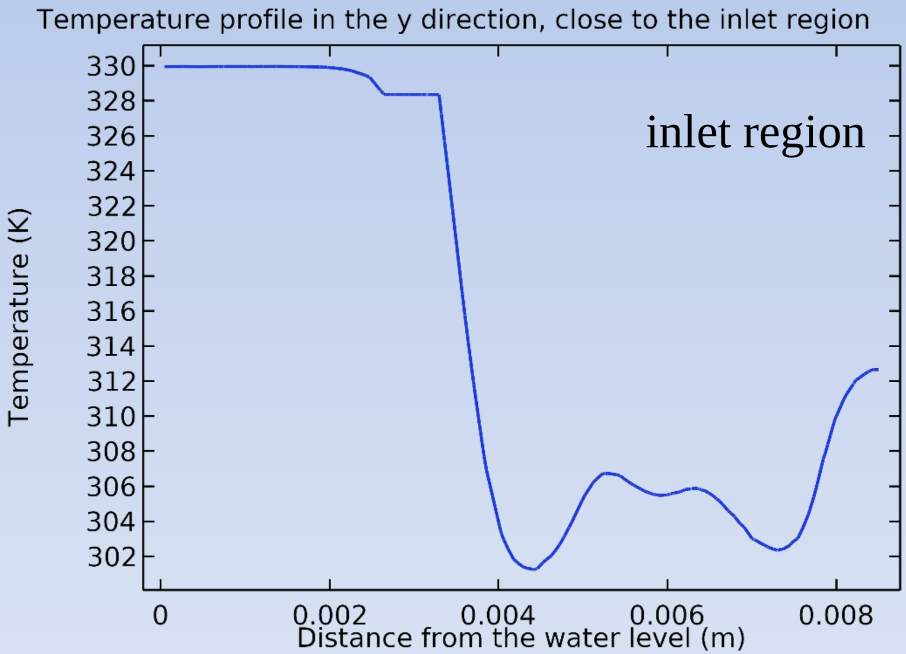
$U_{in,a}$ = 1.5 m/s, $U_{in,w}$ = 0.05 m/s, $T_{in,a}$ = 300 K, $T_{in,w}$ = 330 K , ϑ = 92.01%.

Numerical results: temperature profiles in the *y* vertical direction

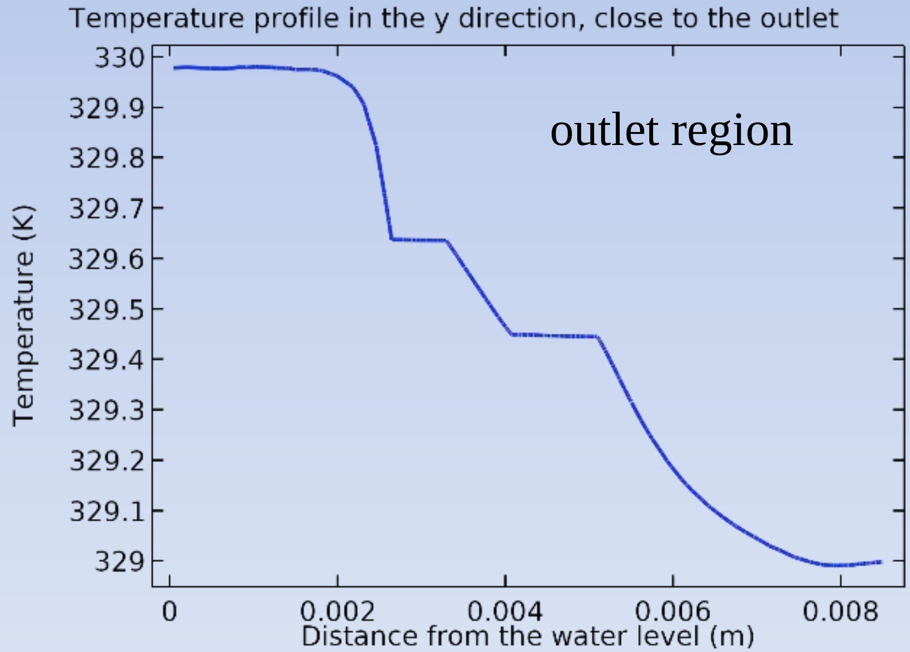


on a longitudinal plane placed in the middle (*z*=0.026m) of the heat exchanger section

x= 0.0135 m

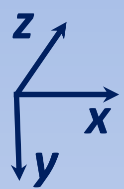


x= 0.0328 m



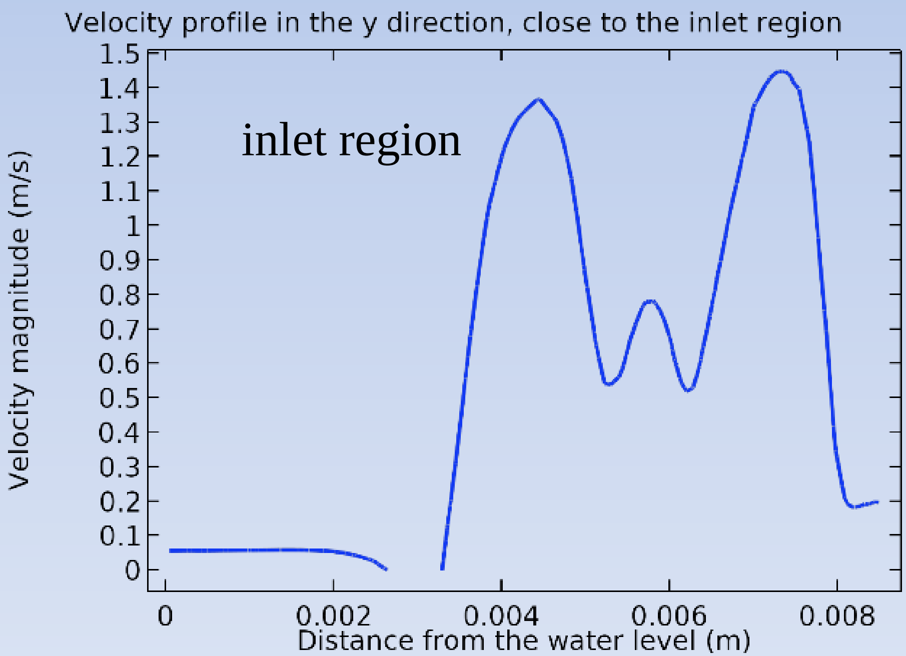
Uin,a = 1.5 m/s, *Uin,w* = 0.05 m/s, *Tin,a* = 300 K, *Tin,w* = 330 K , *ϑ* = 92.01%.

Numerical results: velocity profiles in the *y* vertical direction

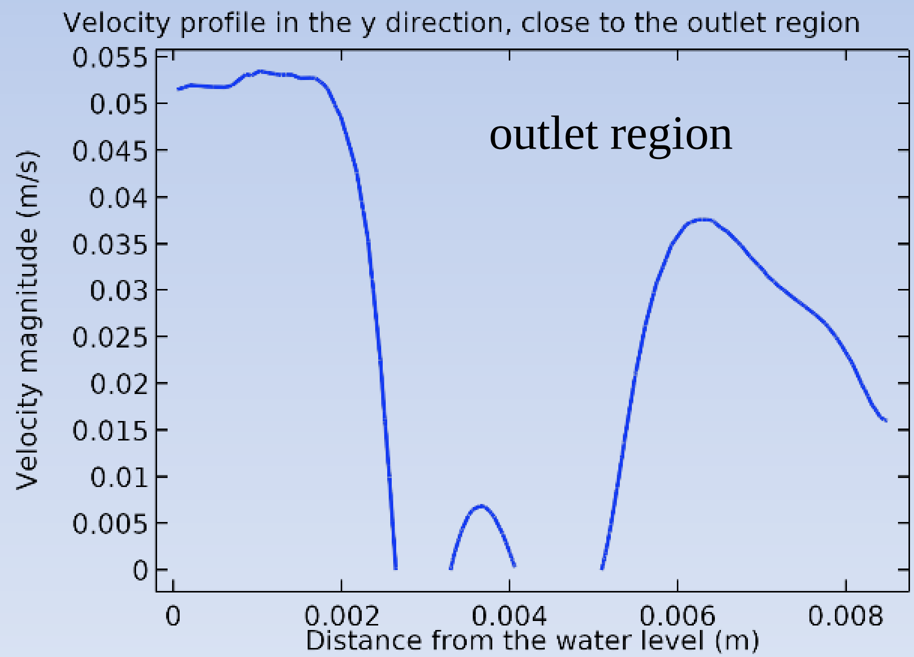


on a longitudinal plane placed in the middle (*z*=0.026m) of the heat exchanger section

x= 0.0135 m



x= 0.0328 m



Uin,a = 1.5 m/s, *Uin,w* = 0.05 m/s, *Tin,a* = 300 K, *Tin,w* = 330 K , ϑ = 92.01%.

Conclusions

- The numerical findings of the simulations show that the computational model developed with COMSOL Multiphysics® is effective for modelling the conjugate flow and heat transfer process through a 3D open-cell aluminium foam.
- The results prove that the energy transfer of the exchanger highly depends on the flow structure, taking advantage of the material's high porosity and large specific surface area.
- The computational model is able to capture the main properties of the coupled heat and fluid flow and can be considered a valid approach to evaluate open-cell metal foams’ performance for heat transfer applications.
- According to these results, we foresee to carry out developments of the modeling work by using CAD of real open-cell foams and evaluating the efficiency of heat exchangers in terms of pressure drop and transferred energy.

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