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Solar Cell Cooling and Heat Recovery in a Concentrated Photovoltaic System

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Outline

- The REET research unit
- CPVT systems
- Heat exchanger: prototype and geometry details
- Model implementation
- Results
- Conclusions

The REET Unit at FBK

REET: Renewable Energies and Environmental Technologies

Topics:

- Solar energy
- Non-ionizing radiations
- Biomass
- Geothermal energy

+

Applied research
in collaboration with
companies

Methods:

- Experimental activity
- Numerical simulations
- Partner collaborations

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CPV systems

PV: photovoltaics
CPV: concentrated PV

CPV possible *advantages*:

- substitute part of the cell area with inexpensive optics → save money to lower system costs or to use more efficient cells
- increase system efficiency with two axis tracking

CPV possible *disadvantages*:

- more complex system, due to tracking and optics
- no diffused radiation capturing
- optical losses
- thermal issues

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Thermal “issues”?

Thermal issues could be transformed in thermal energy gain!
CPVT: CPV + thermal energy recovery

Heat recovery is being widely considered for flat plates (PVT). In CPV systems, heat recovery can solve the problem of cooling.

But…

A compromise is needed for the operating temperature:
as low as possible for cells, as high as possible for heating purposes.

Crucial point: identification of a suitable heating application.

CPVT components

Tracking system: electric motor (e.g., step motor) and gears.

Optics: primary optics (e.g., Fresnel lenses) and secondary optics (e.g., prism).

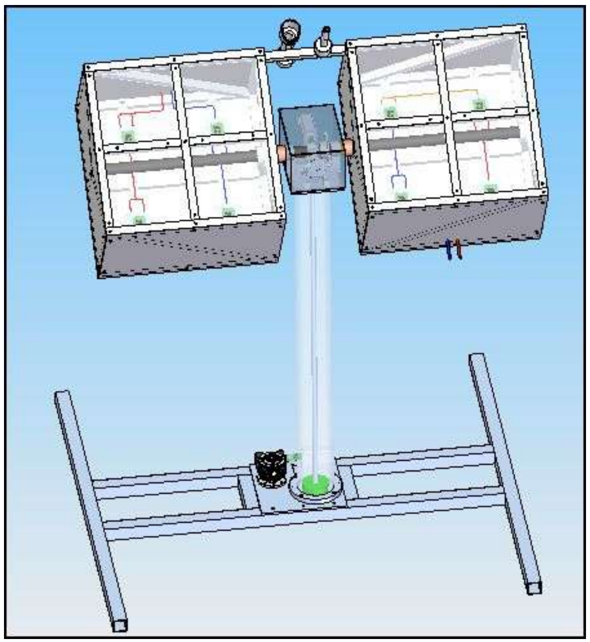
Cells and packaging: PV cells (e.g., triple junction cells) and substrate (e.g., insulated metal substrate).

Heat exchange: exchanger (e.g., micro-channel heat exchanger) and thermal circuit.

Data acquisition and control: sensors (e.g., radiation and temperature sensors), hardware (e.g., PLC), software (tracking algorithm, MMPT algorithm, thermal management algorithm).

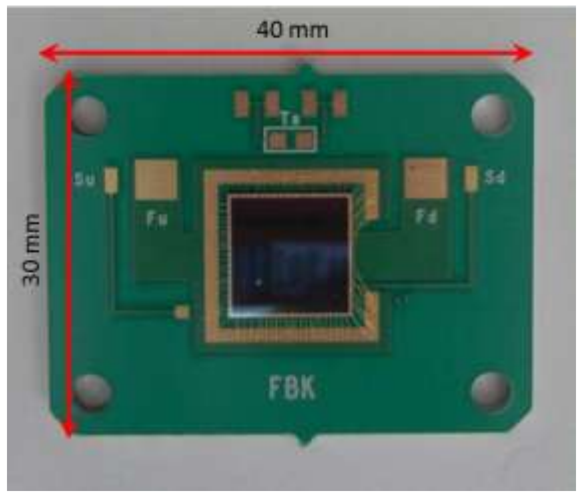
A CPVT prototype

Tracking system and optics (**Bologna University**)



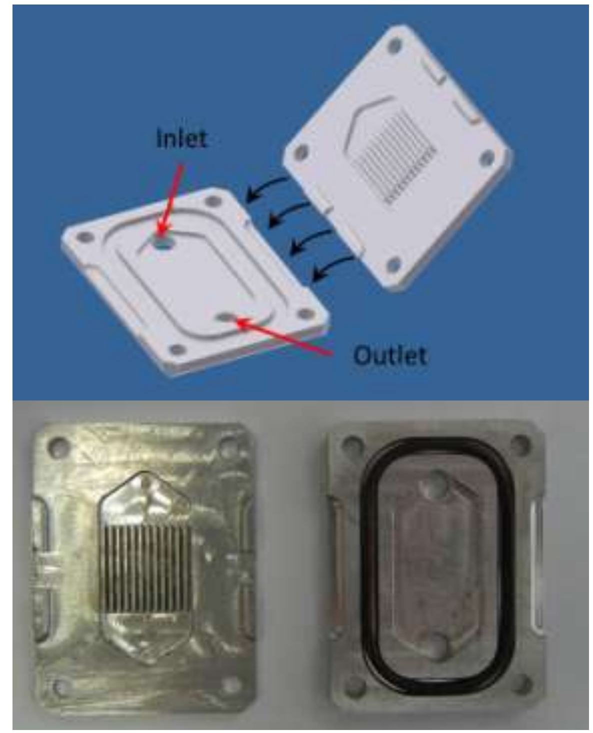
Fresnel lenses, 30 cm x 30 cm

Solar cell and packaging (**FBK**)



Mono-crystalline Si cells, 1 cm x 1 cm, optimized for 160 suns ($\eta \sim 20$ %)

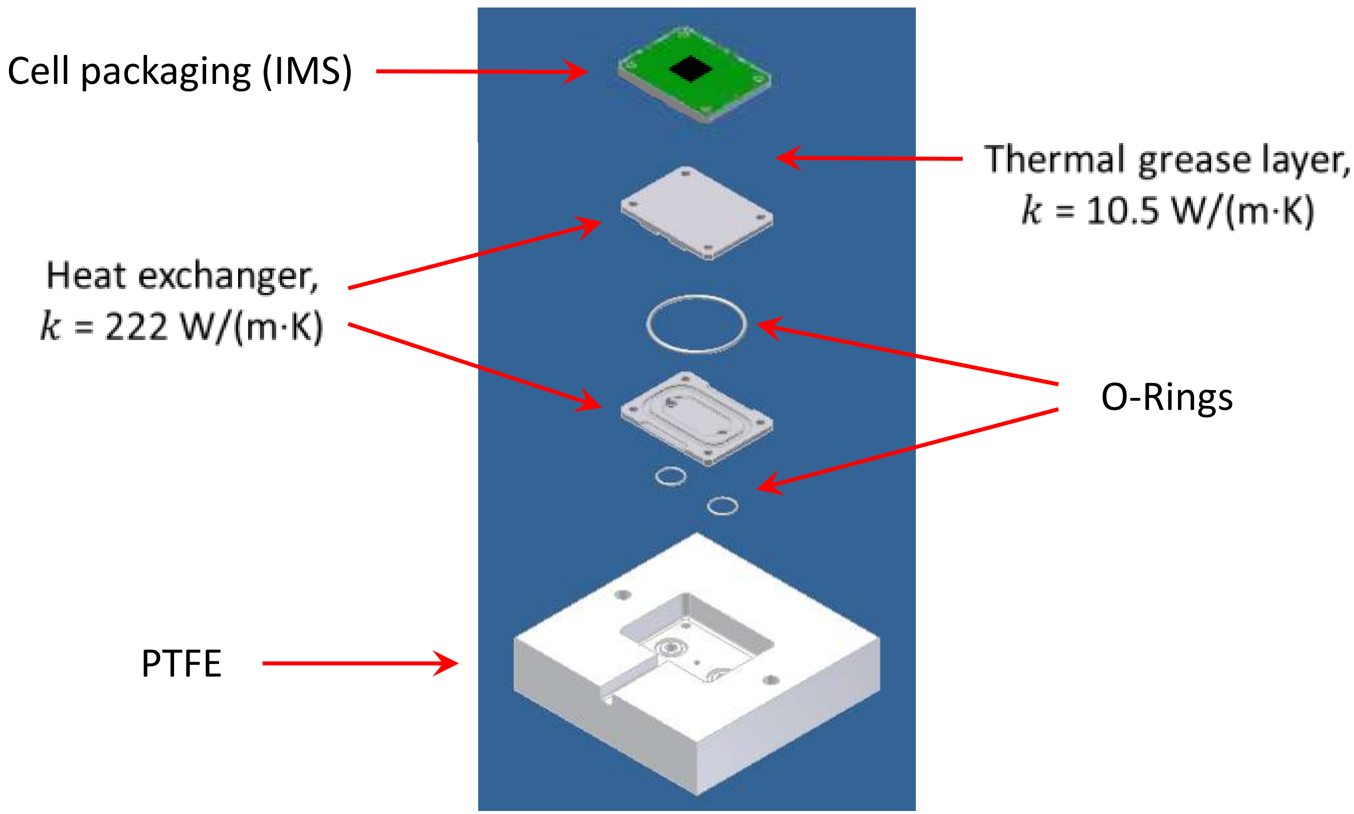
Micro-channel heat exchanger (**FBK**)



Array of rectangular micro-channels, milled in aluminum

Heat exchange kit

Heat exchanger mounting



Comsol model implementation

Navier-Stokes equations, incompressible fluid (water).
Heat transfer in solids and fluids.

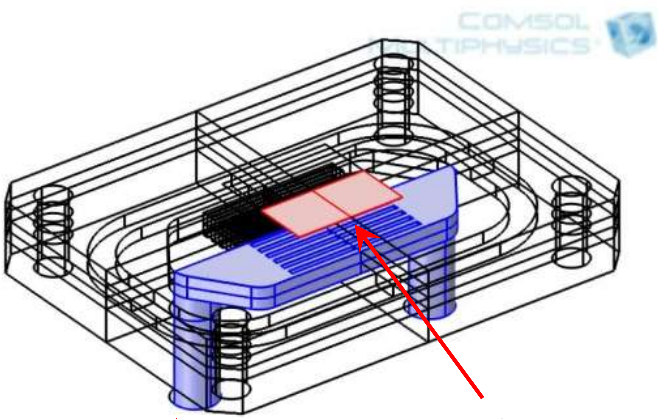
Solver. PARDISO, highly non-linear problem.

Mesh, element order. Unstructured tetrahedral mesh elements (overall heat exchanger), mapped+swept mesh elements (single channel), linear.

Boundary conditions.
Fluid-dynamics. Walls: no slip b.c.'s. Inlet and outlet: velocity-pressure.
Heat transfer. Insulation, temperature, heat flux, thin insulating layer.

Heat exchanger

Symmetry → reduced geometry



Heat flux: 12.8 W/cm^2 (160 suns = 16 W/cm^2, minus 20 % electric efficiency)

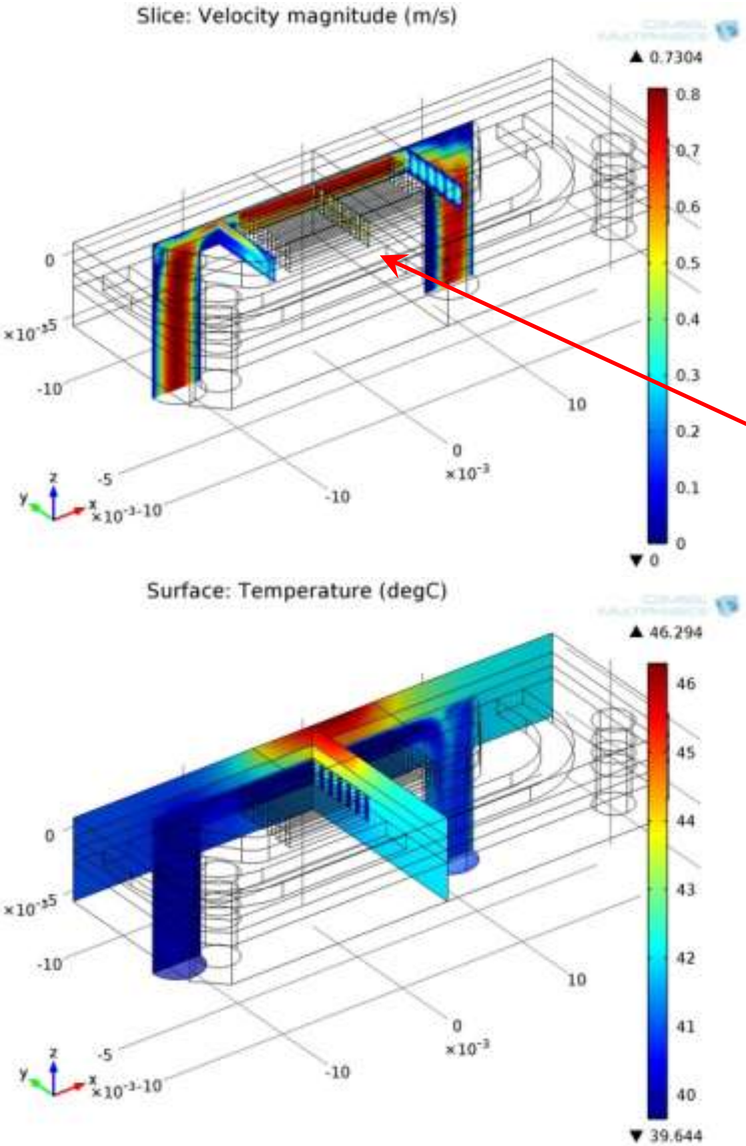
Inlet temperature: 40 °C

Flow rate: 5 ml/s (water), distributed in 13 channels

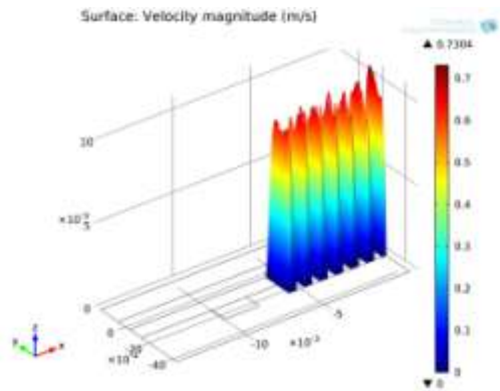
Channel cross section: 0.5 mm x 2 mm (D_h = 800 μm)

Thermal grease layer: 100 μm

Heat exchanger results

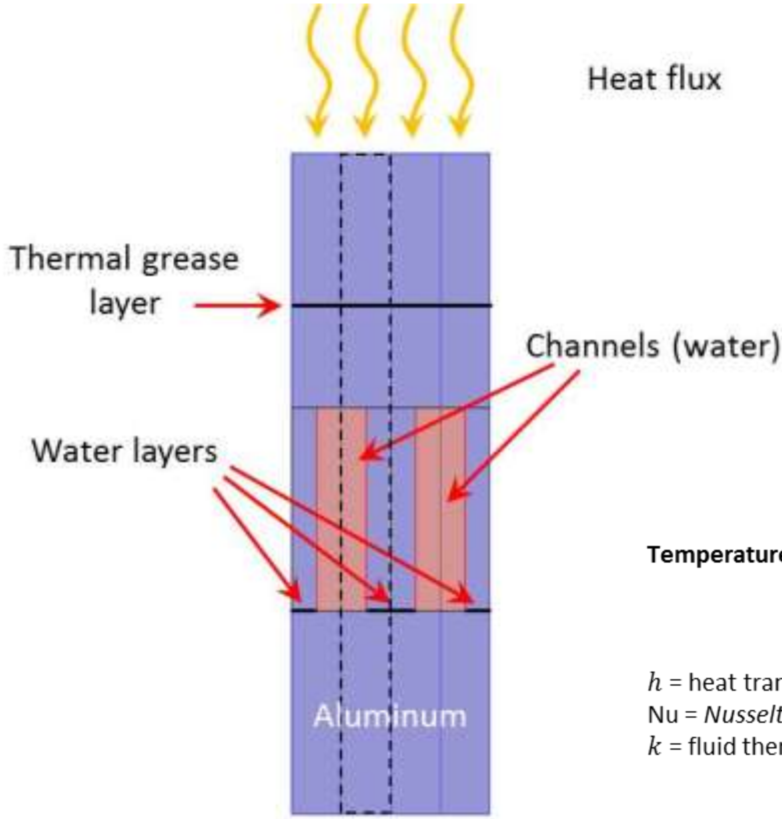


- Balanced flow rate within the channels
- About 6 K of difference between fluid inlet and maximum aluminum temperature (ΔT_{HE} = 4 K, $\Delta T_{\mathrm{IMS-Al}}$ = 2 K)
- $\Delta p \sim$ 6.6 mbar



Velocity distribution within the channels

Single channel geometry



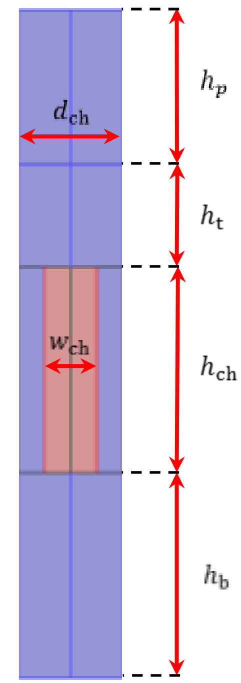
Geometry: array of parallel channels with rectangular cross section
Large number of channels
→ far from array border solution resembles an *infinite* array
→ **symmetry**

Heat flux $q_{\rm rad}$
→ completely absorbed by the fluid (water) flowing in the channels
→ *spread* on the channel walls (possibly excluding bottom ones)
Surface ratio

$$r_{\rm surf} = d_{\rm ch}/(w_{\rm ch} + 2h_{\rm ch}) = 0.22$$

Compare with *straight circular channel* with $D = D_{\rm h,ch}$ and constant radial heat flux $q_{\rm ch} = 0.22\, q_{\rm rad}$

Channel *hydraulic diameter*:
$$D_{\rm h,ch} = 4A_{\rm ch}/P_{\rm ch} = 2\, w_{\rm ch} h_{\rm ch}/(w_{\rm ch} + h_{\rm ch}) = 0.8 \text{ mm}$$



Temperature difference $\Delta T_{\rm w-b}$ between wall and fluid bulk

$$\Delta T_{\rm w-b} = q_{\rm ch}/h$$

h = heat transfer coefficient
Nu = *Nusselt* number
k = fluid thermal conductivity

$$h = {\rm Nu}\; k/D_{\rm h,ch}$$

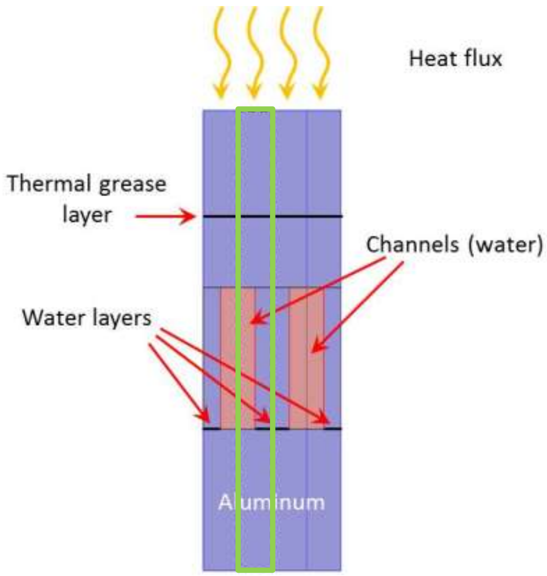
Laminar flow: Nu = 48/11 = 4.36

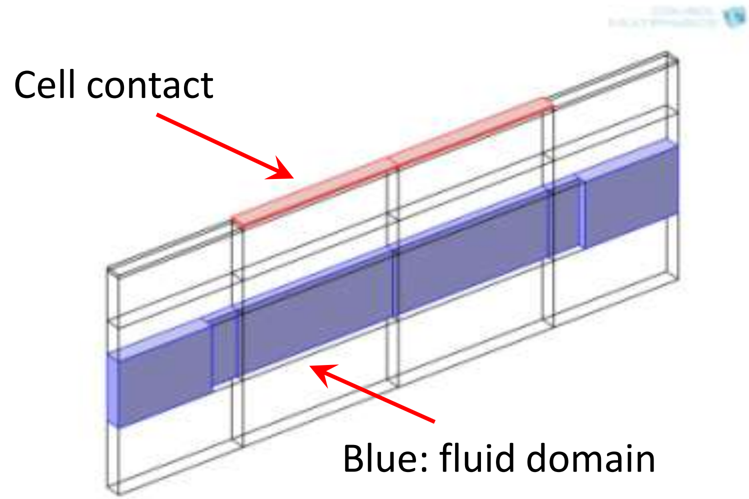
Water: k = 0.6 W/(m·K) $\Longrightarrow$ h = 3273 W/(m^2·K)

Incident flux $q_{\rm rad}$ = 12.8 W/cm^2 $\Longrightarrow$ $q_{\rm ch}$ = 2.82 W/cm^2 $\Longrightarrow \Delta T_{\rm w-b}$ = 8.6 K

Single channel geometry

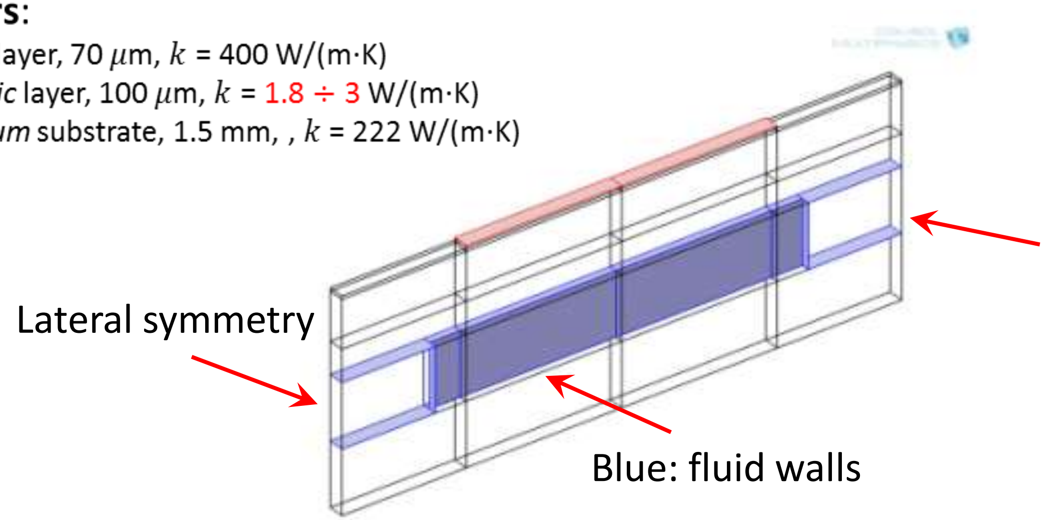
Exploit symmetry



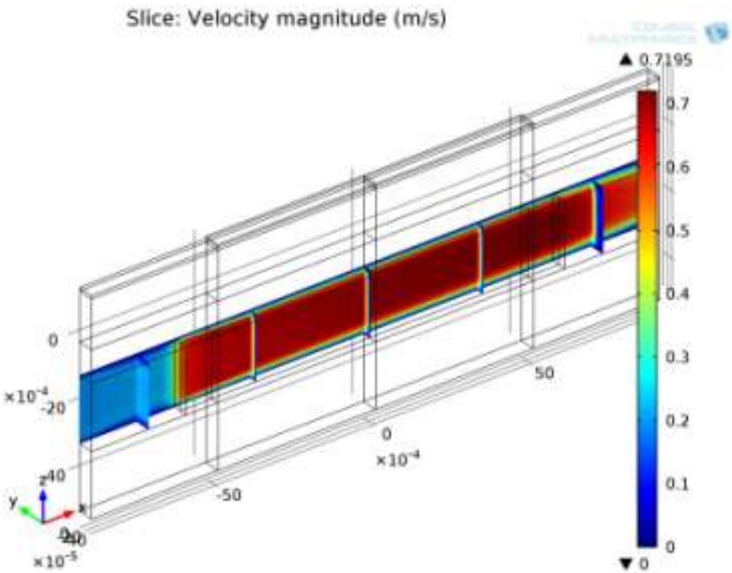


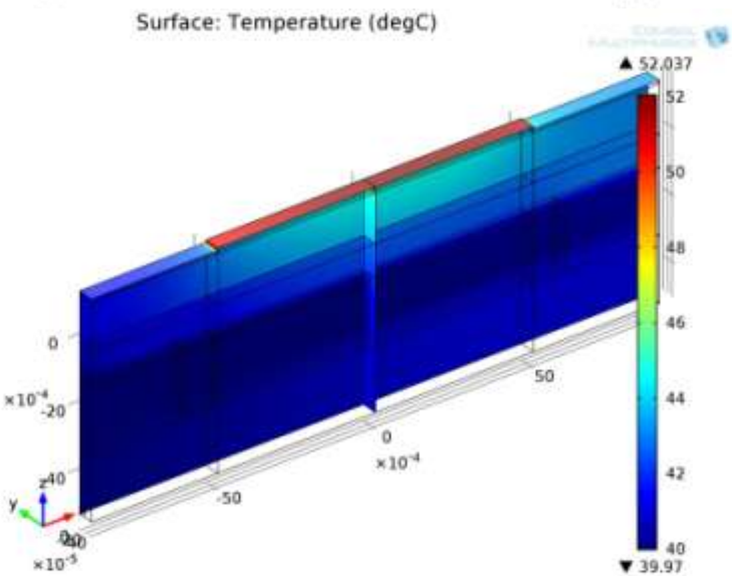
IMS layers:

- *copper* layer, 70 μm, k = 400 W/(m·K)
- *dielectric* layer, 100 μm, k = 1.8 ÷ 3 W/(m·K)
- *aluminum* substrate, 1.5 mm, , k = 222 W/(m·K)

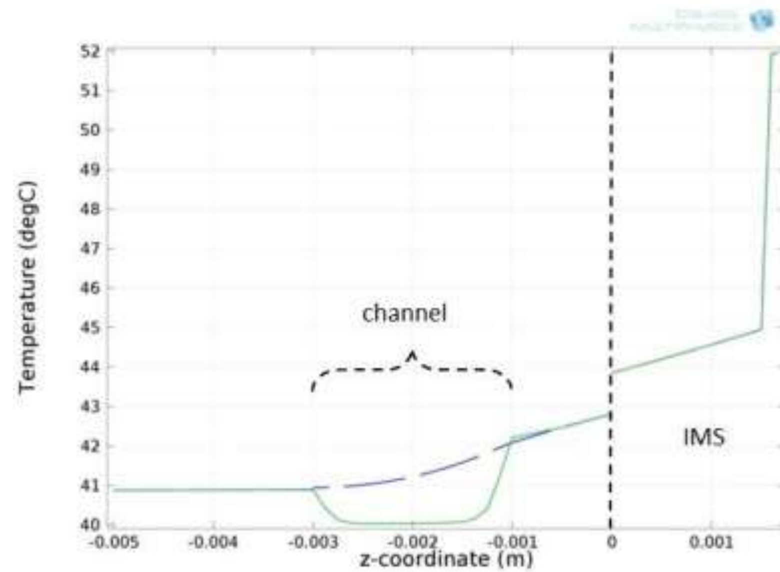


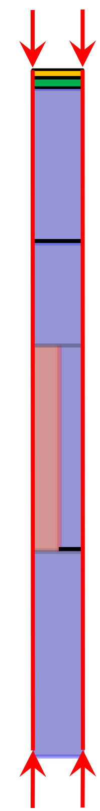
Single channel results





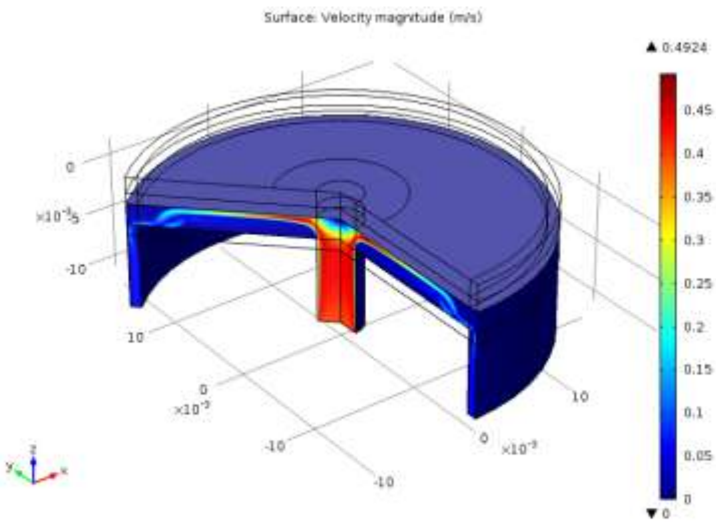
- About 12 K of difference between fluid inlet and maximum cell temperature (ΔT_{HE} = 4 K, $\Delta T_{\mathrm{IMS-Al}}$ = 2 K, $\Delta T_{\mathrm{IMS-ins}}$ = 6 K)
- Uniform inflow velocity corresponding to half channel, $\Delta p \sim$ 4.8 mbar

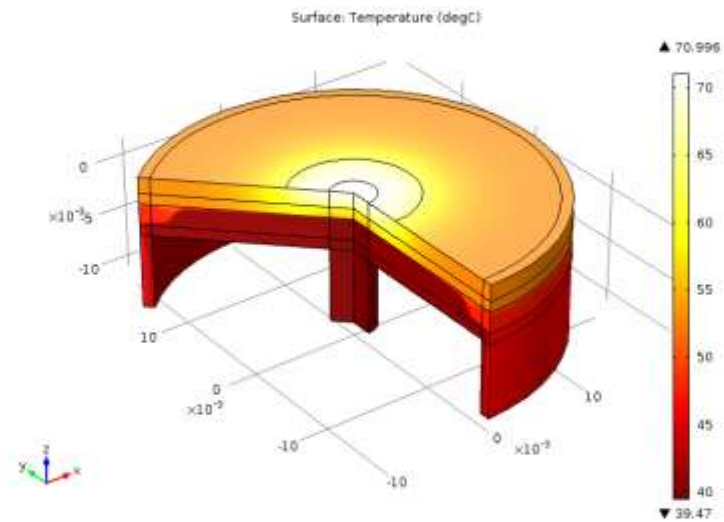




Preliminary results

Impinging jets:
promising solution for **triple junction cells**
(1000 suns, ~ 70 W/cm^2)





Conclusions

- Micro-channel heat exchanger geometry: suitable for Si-cells with IMS packaging (provide manufacturing costs can be lowered)
- Cell packaging: thermal bottleneck given by dielectric layer
- Triple junction cells: improved thermal solutions have to be employed
- Comsol results (in reasonable agreement with analytical estimates) will be validated experimentally

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Technical Info

Machine. Processor: double six-core, 2.66 GHz. RAM: 96 GB.

Number of degrees of freedom.

Micro heat exchanger:

• Half-exchanger symmetry: 2,500,000 dof

Single channel:

• Array-like symmetry: about 200,000 dof