BM@N-STS Electronics Cooling Theoretical Calculations & CFD Simulations

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Coordination Meeting on the GSI-JINR Roadmap Agreement
28/04/2021 – Virtual Meeting

EBERHARD KARLS UNIVERSITÄT TÜBINGEN
MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut
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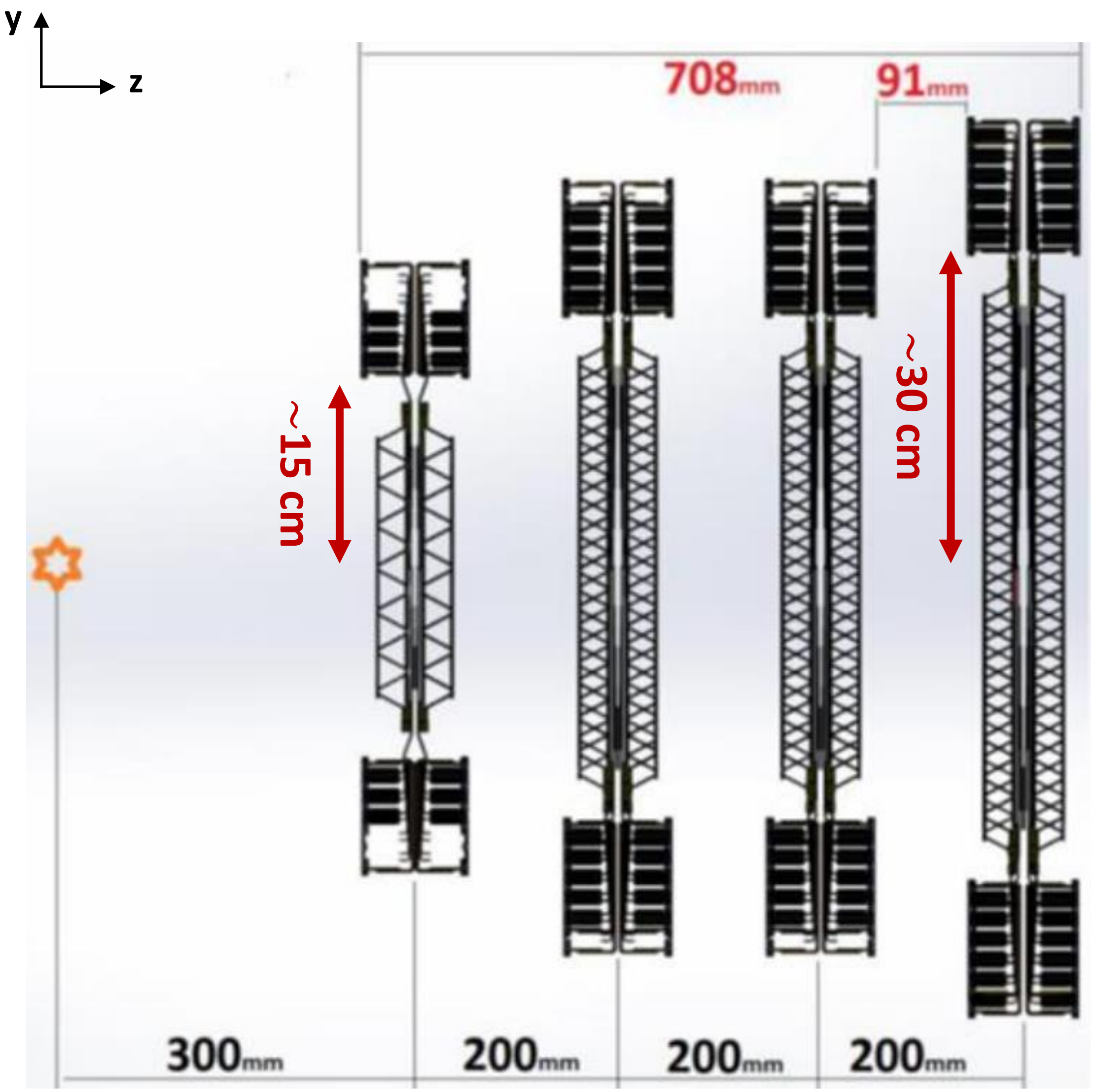
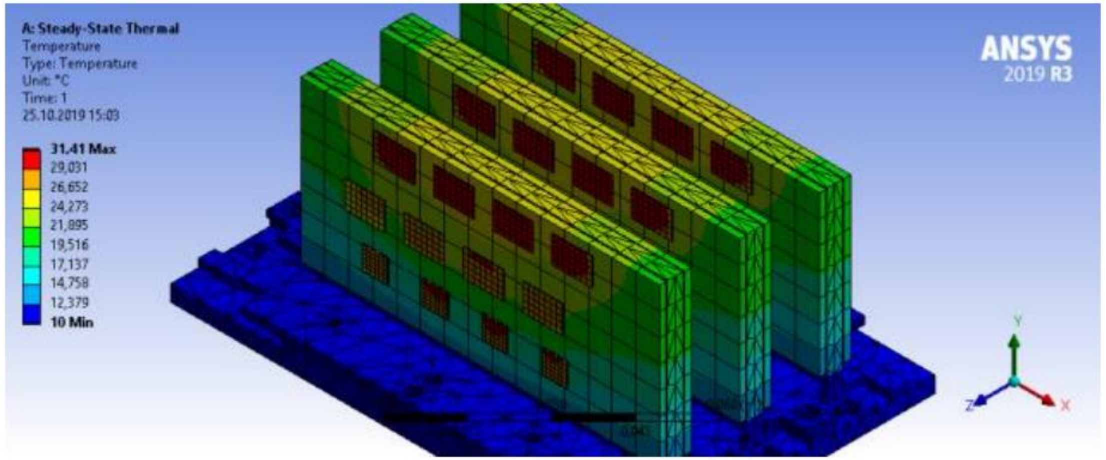
Boundary Conditions

How Cold Should The Cooling Plates/C-Frames Be?



- **Given the expected radiation dose on the innermost BM@N silicon sensors, it is foreseen to operate them at +15°C**
- **So, the FEE located only 15 to 30 cm away should be at similar temp. (~15°C) to avoid any unwanted heat transfer to the silicon sensors**



Coolant Temp. = 10°C
Cooing Plate Temp. ≈ 10°C
ASIC Temp. = 31.4°C

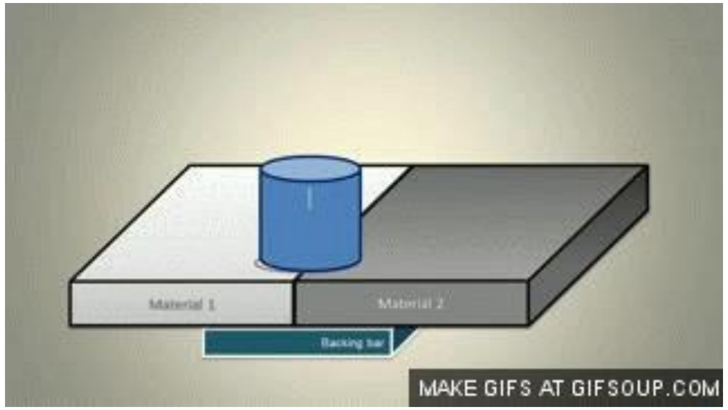
By assuming the FEB temp. varies linearly with the temp. of the coolant and cooling plate,
Cooling plate must be ~ -5°C to obtain ~ +15°C ASIC temp.

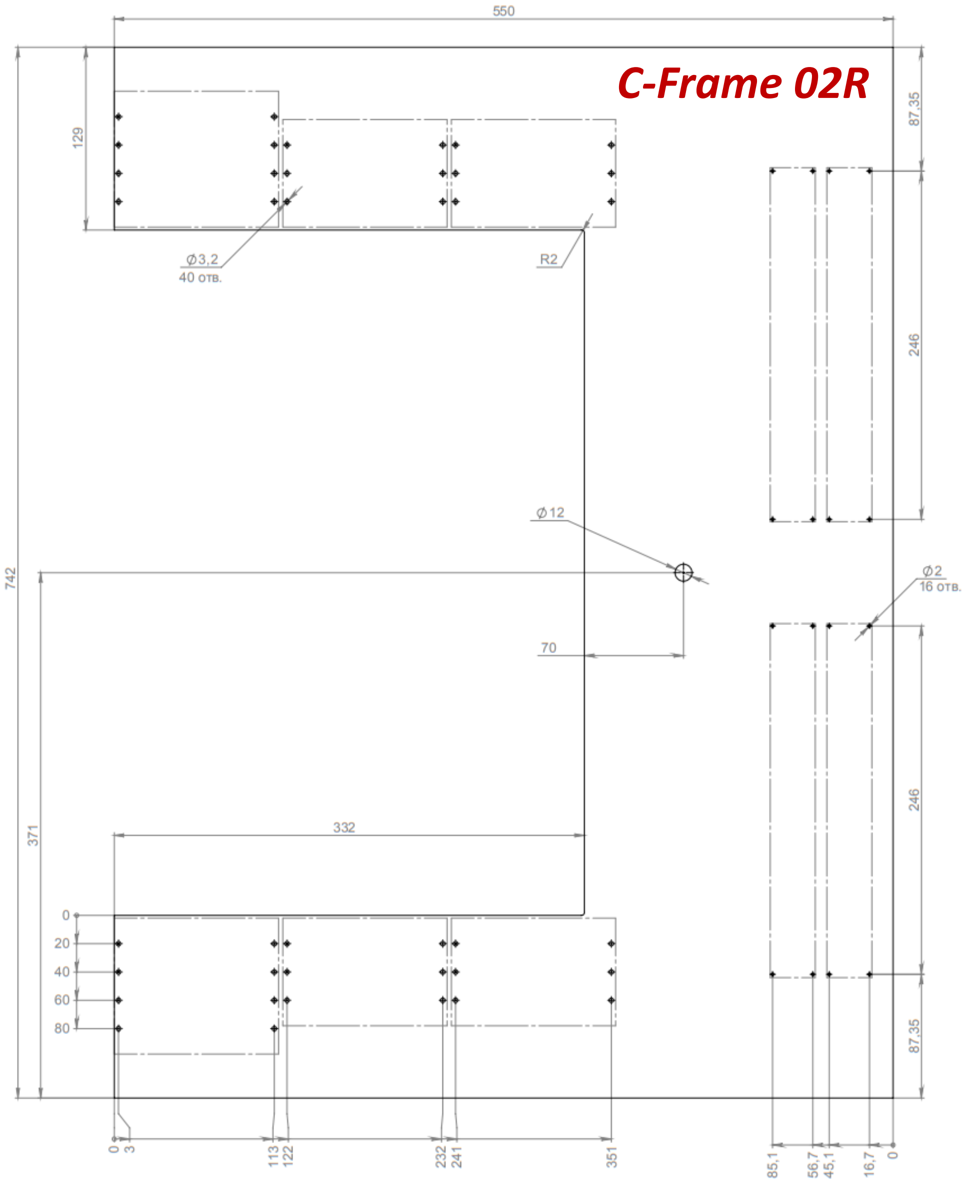
Manufacturing Of Cooling Plates/C-Frames

Friction Stir Welding

Technology proposed for CBM-STS cooling plates by CoolTec Electronic GmbH, and a potential solution for BM@N-STS

https://www.cooltec.de/produkte/cold-plates.php



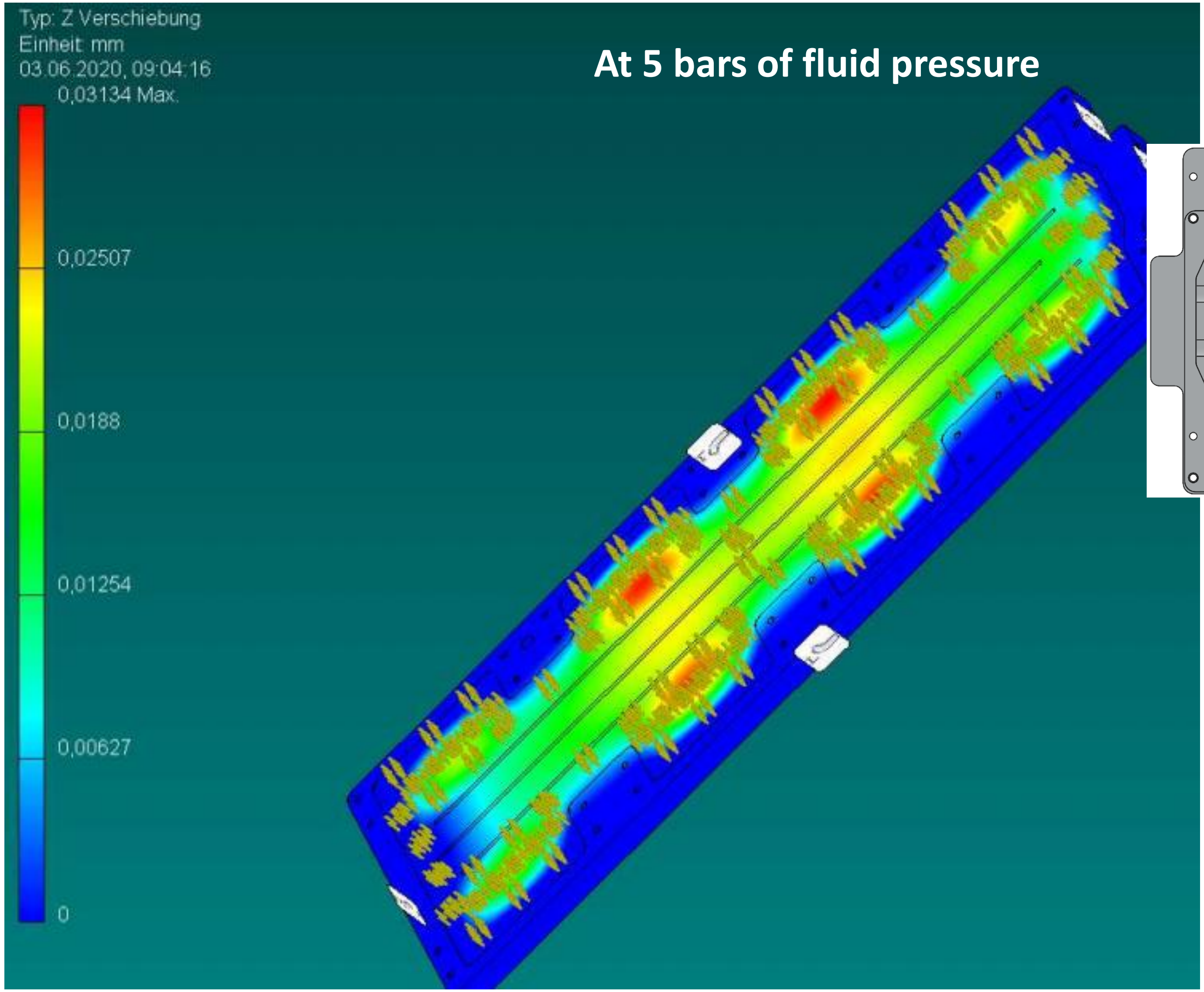


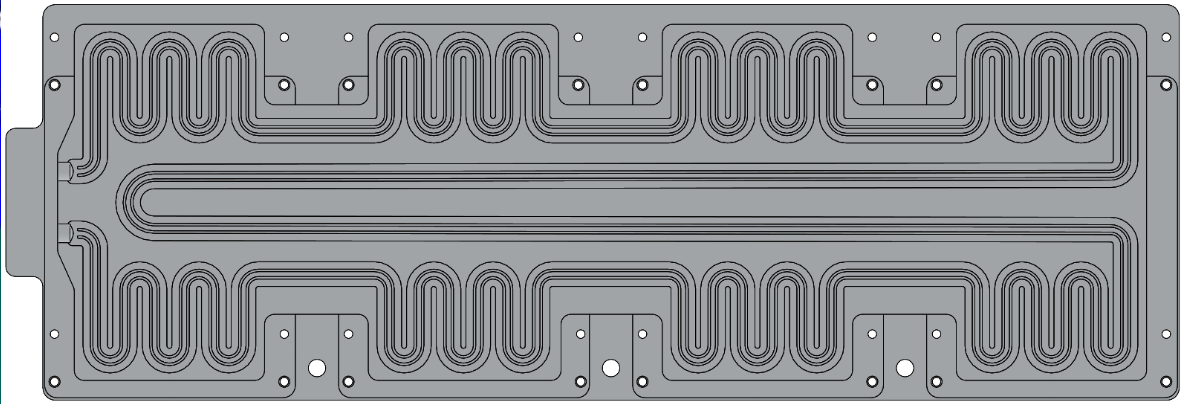
Please note that the C-Frame dimensions are ~ 1m²

Are C-Frames of these dimensions even manufacturable with this technology? Can they stand up to 2-3 bar of fluid pressure?

Collaboration with an industrial partner is a must before proceeding any further with any design freeze!

POTENTIAL LEARNINGS FROM THE EXPERIENCES OF CBM-STS





The milled-channels have certain manufacturing boundary conditions which must be followed. And has to be complemented with our requirements –

- **Power dissipation**
- **Coolant temperature**
- **Coolant flow rate**
- **Pressure drop**
- **…**

Potential Coolants
[1] 3M Novec 649
[2] WAter-Glycol Mixture

[1] Introduction To 3M Novec 649

Radiation hard (resistant to gamma radiation > 10 kGy). So minimal production of radiation byproducts, which otherwise could block cooling lines or cause corrosion!

Properties Description

Composition of 3M™ Novec™ 649 Fluid	
Dodecafluoro-2-methylpentan-3-one	99.0 mole %, minimum
Chemical Formula	$CF_3CF_2C(O)CF(CF_3)_2$

Typical Physical Properties

	3M™ Novec™ 649 Fluid
Boiling Point(°C)	49
Pour Point (°C)	-108
Molecular Weight (g/mol)	316
Critical Temperature (°C)	169
Critical Pressure (MPa)	1.88
Vapor Pressure (kPa)	40
Heat of Vaporization (kJ/kg)	88
Liquid Density (kg/m^3)	1600
Coefficient of Expansion (K^{-1})	0.0018
Kinematic Viscosity (cSt)	0.40
Absolute Viscosity (cP)	0.64
Specific Heat (J/kg-K)	1103
Thermal Conductivity (W/m-K)	0.059
Surface Tension (mN/m)	10.8
Solubility of Water in Fluid (ppm by wt)	20
Dielectric Strength, 0.1" gap (kV)	>40
Dielectric Constant @ 1kHz	1.8
Volume Resistivity (Ohm-cm)	10^{12}
Global Warming Potential (GWP)	1

Usable down to -108°C (→ Pour Point)

Lower heat capacity w.r.t. water. So higher flow would be required. (→ Specific Heat)

Green, which ensures long-term availability (→ Global Warming Potential)

CBM

Potentially useful reference for any calculations or simulations

REFPROP (Novec 649, 1230) - NIST Reference Fluid Properties (DLL version 10.0) - [5: Novec 649, 1230: V/L sat. T=-40, to 20, °C]

File Edit Options Substance Calculate Plot Window Help Cautions

	Temperature (°C)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Cv (kJ/kg-K)	Vapor Cv (kJ/kg-K)	Liquid Cp (kJ/kg-K)	Vapor Cp (kJ/kg-K)	Liquid Therm. Cond. (mW/m-K)	Vapor Therm. Cond. (mW/m-K)	Liquid Kin. Viscosity (cm²/s)	Vapor Kin. Viscosity (cm²/s)	Liquid Prandtl	Vapor Prandtl
1	-40,000	1785,7	0,15493	0,87562	0,79741	1,0940	0,82401	69,747	7,7559	0,010941	0,49421	30,643	0,81348
2	-35,000	1772,1	0,22258	0,87448	0,79938	1,0922	0,82608	68,826	8,0449	0,0099244	0,35298	27,908	0,80675
3	-30,000	1758,6	0,31366	0,87371	0,80152	1,0908	0,82836	67,904	8,3360	0,0090365	0,25708	25,527	0,80128
4	-25,000	1744,9	0,43418	0,87328	0,80386	1,0898	0,83086	66,980	8,6293	0,0082565	0,19066	23,441	0,79705
5	-20,000	1731,2	0,59112	0,87319	0,80639	1,0893	0,83360	66,056	8,9248	0,0075682	0,14382	21,606	0,79404
6	-15,000	1717,4	0,79249	0,87343	0,80913	1,0892	0,83658	65,131	9,2226	0,0069581	0,11021	19,983	0,79224
7	-10,000	1703,5	1,0473	0,87400	0,81207	1,0895	0,83982	64,208	9,5225	0,0064151	0,085706	18,542	0,79165
8	-5,0000	1689,4	1,3659	0,87486	0,81523	1,0902	0,84333	63,285	9,8248	0,0059299	0,067575	17,258	0,79225
9	0,00000	1675,3	1,7593	0,87603	0,81859	1,0912	0,84711	62,363	10,129	0,0054949	0,053969	16,108	0,79404
10	5,0000	1661,0	2,2402	0,87749	0,82218	1,0927	0,85117	61,443	10,437	0,0051036	0,043623	15,076	0,79702
11	10,000	1646,6	2,8222	0,87922	0,82598	1,0945	0,85553	60,524	10,746	0,0047505	0,035659	14,146	0,80118
12	15,000	1632,0	3,5202	0,88123	0,82999	1,0967	0,86018	59,608	11,059	0,0044309	0,029456	13,305	0,80652
13	20,000	1617,2	4,3502	0,88350	0,83422	1,0993	0,86514	58,700	11,375	0,0041409	0,024572	12,542	0,81304

[1] Commercial Availability Of 3M Novec 649

Dear Kshitij,

thanks for your request. Here you find the quote (free to be changed) for Novec 3M™ Novec™ 649 according to your demand of aprox. 300 kg:

Produkt	Gebinde	Preis (€/lbs)	Preis (€/kg)	Preis/VPE in €	Katalog-Nr.
Novec 649	38 lbs	26,72	58,33	1.015,36	7100025284
Novec 649	353 lbs	24,08	52,56	8.500,24	7100027553
Novec 649	661,5 lbs	23,72	51,79	15.690.78	7100027554

Next year 1st of Feb it will increase 2%

With these figures you can calculate, about size, amount and who will be the purchaser we will talk when it becomes a real demand.

Mit freundlichen Grüßen, best regards

Thomas Rannersberger

3M Science. Applied to Life.™

Thomas Rannersberger | Dipl.-Phys. (FH) | Vertriebsingenieur

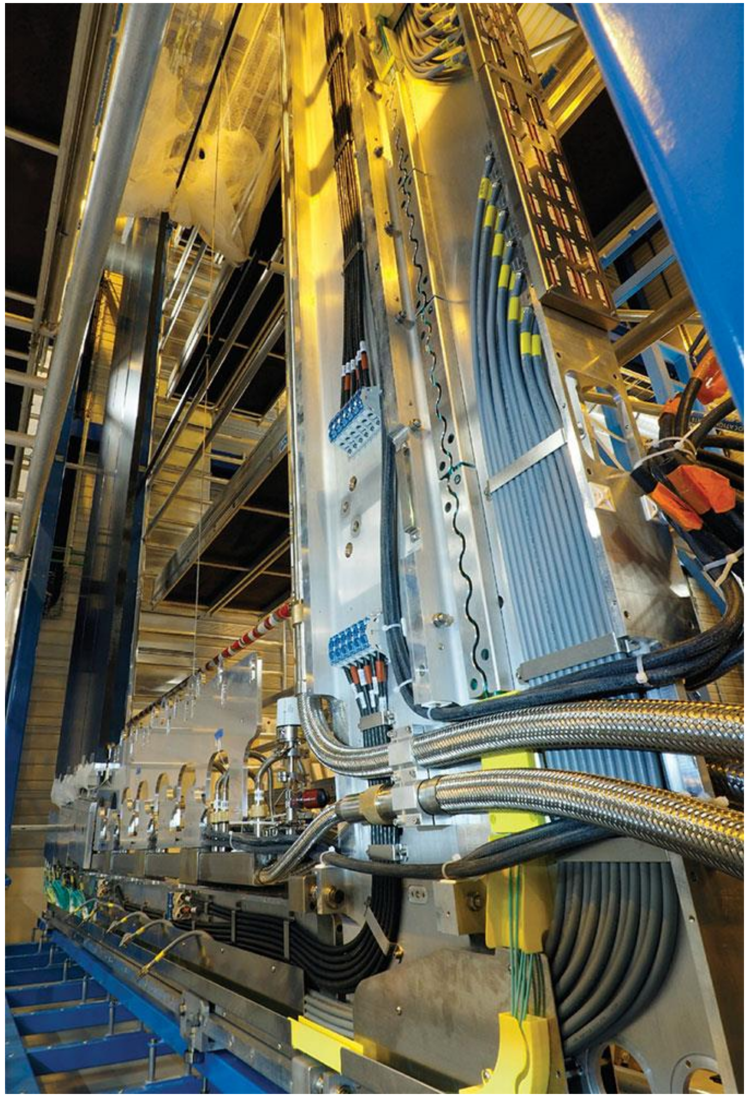
Chemicals and Semiconductor Materials, 3M EMSD

Central Europe Region
3M Deutschland GmbH, Carl-Schurz-Str. 1, D-41453 Neuss,

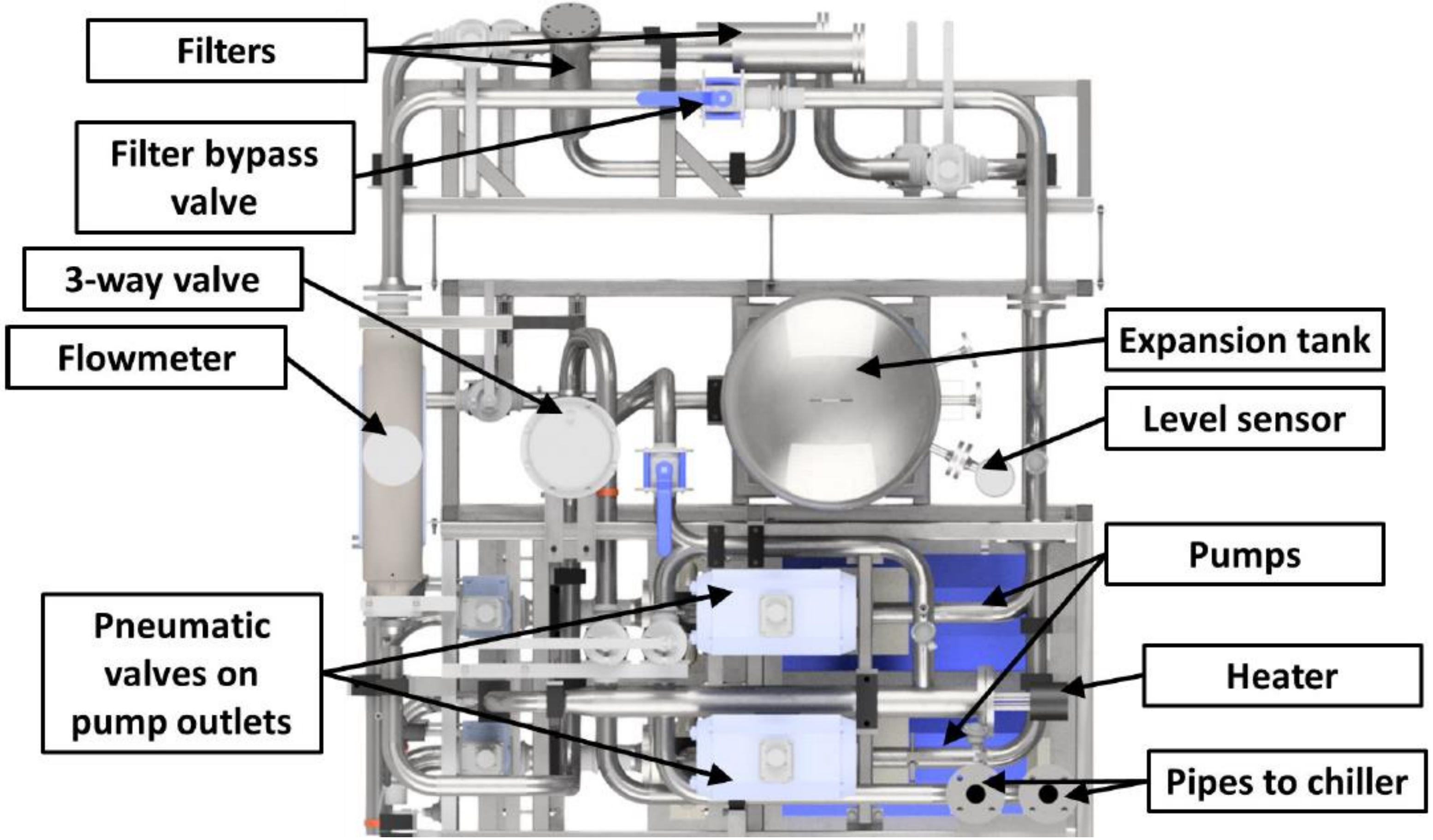
Mobile: +49 160 9098 5918
tRannersberger@3M.com www.novec.de

- **Higher quantities could be purchased directly from 3M (€ 50-60/kg)**
- **Lower quantities are readily available in Germany from Ionic Liquid Technologies – IoLiTec (Heilbronn DE)**

[1] Where In Use So Far?



LHCb SciFi Tracker



[1] (Near) Future: CBM-STS Baby Cooling Plant

- **Baby Cooling Plant delivered at GSI on 18.12.2020**
- **7.5 kW cooling capacity at -40°C**
- **Commissioning to be done within 2 months**

compact KÄLTETECHNIK

Klima-Kälte-Reinraumtechnik GmbH

[2] Fluid Properties – Water-Glycol Mixture

Hopefully doesn't need any introduction ;-)

https://detector-cooling.web.cern.ch/data/Table%208-3-1.htm

Table 8-3-1 - Properties of mixture Water/Glycol

Extract from VDI-Warmeatlas Dd 17- VDI-Verlag GmbH, Dusseldorf 1991

Substance and % by volume in mixture	Minimal working temperature [°C]	Temperature [°C]	Density [kg/m^3]	Specific heat [kJ/kg.K]	Thermal conductivity [W/m.K]	Dynamic viscosity X10^{-3} [N.s/m^2]	Cinematic viscosity X10^{-6} [m^2/s]
Monoethylenglycol C2H4(OH)2 20	-10	-10	1038	3.85	0.498	5.19	5
		0	1036	3.87	0.50	3.11	3
		20	1030	3.90	0.512	1.65	1.6
		40	1022	3.93	0.521	1.02	1.0
		60	1014	3.96	0.531	0.71	0.7
		80	1006	3.99	0.540	0.523	0.52
		100	997	4.02	0.550	0.409	0.41
34	-20	-20	1069	3.51	0.462	11.76	11
		0	1063	3.56	0.466	4.89	4.6
		20	1055	3.62	0.470	2.32	2.2
		40	1044	3.68	0.473	1.57	1.5
		60	1033	3.73	0.475	1.01	0.98
		80	1022	3.78	0.478	0.695	0.68
		100	1010	3.84	0.480	0.515	0.51

https://doi.org/10.1002/bbpc.19840880813

Thermal Conductivity, Density, Viscosity, and Prandtl-Numbers of Ethylene Glycol-Water Mixtures

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Density / Prandtl-Number / Thermal Conductivity / Transport Properties / Viscosity

Thermal conductivity, density, and viscosity of ethylene glycol – water mixtures have been measured. The measurements have been performed in the temperature range from −20°C to 180°C for thermal conductivity, from −10°C to 150°C for density, and from −10°C to 100°C for viscosity. Prandtl-Numbers calculated with the own experimental data and literature values of specific heat capacity are presented in dependence of temperature and concentration.

For Prandtl Number

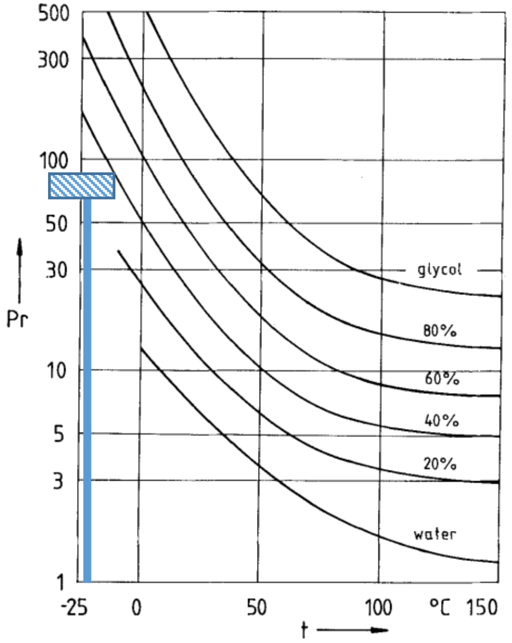


Fig. 4
Prandtl-Number of ethylene glycol-water mixtures

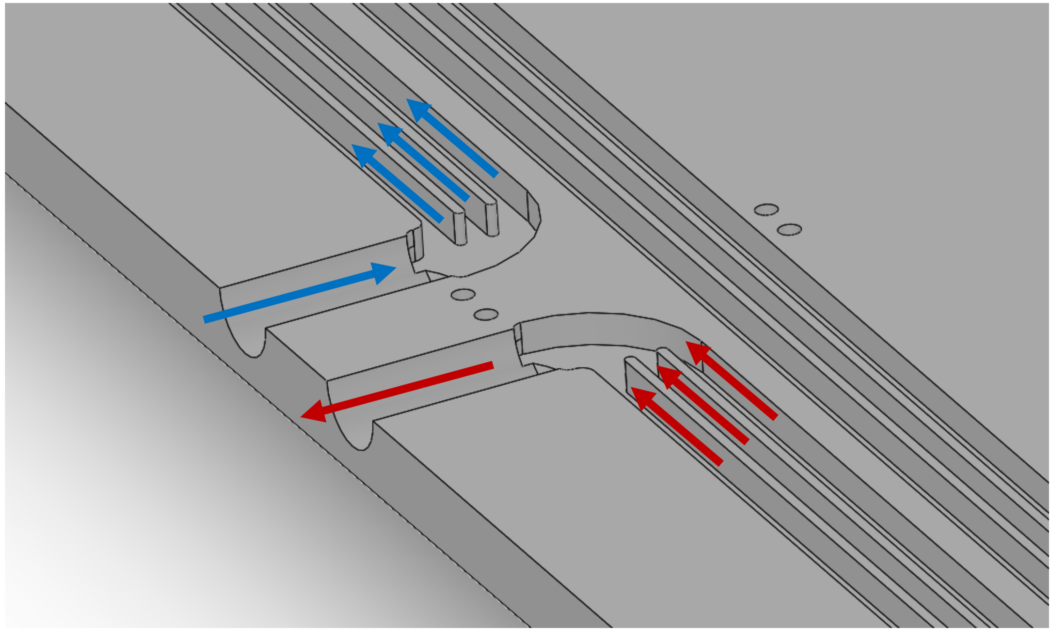
(Approximate) Theoretical Modelling
[1] Pressure Drop
[2] Surface Temp.

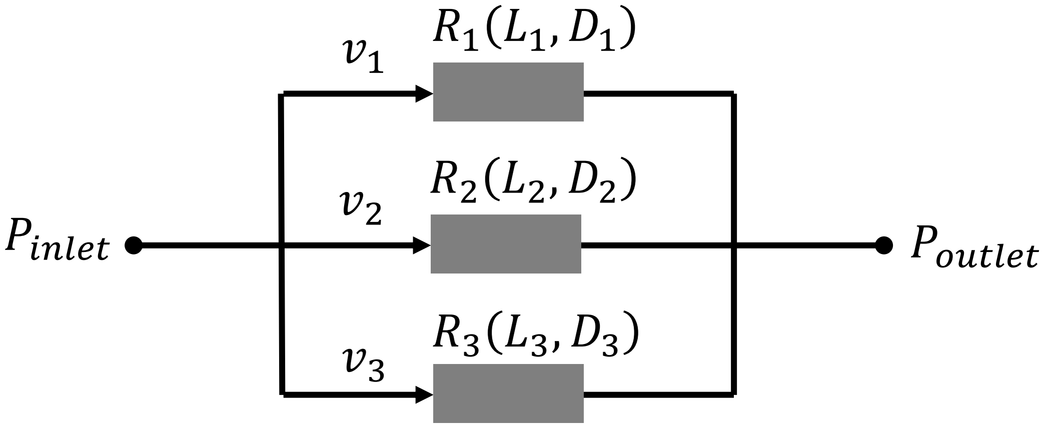
Motivation – Can we theoretically model and predict the pressure drop for the BM@N cooling plates for the given boundary conditions (in terms of fluid type, flow numbers and geometry)?

To calculate the pressure-drop per unit length in a tube, we can use Darcy-Weisbach Equation:

$$\frac{\Delta P}{L} = f_D \cdot \frac{\rho}{2} \cdot \frac{v^2}{D}$$

where, f_D **= Darcy Friction Factor (online tool)**
ρ = Fluid Density [kg/m³]
v = Fluid Velocity [m/s]
D = Hydraulic Diameter [m] = 4 x Area / Perimeter





In the theoretical circuit analogy, individual finned channel represents a flow resistance which the fluid experiences. And since there are three channels running in parallel, they are analogous to three flow resistances connected in parallel.

[1] Theoretical Modelling – Pressure Drop

To calculate the pressure-drop per unit length in a tube, we can use Darcy-Weisbach Equation:

$$\frac{\Delta P}{L} = f_D \cdot \frac{\rho}{2} \cdot \frac{v^2}{D}$$

where, f_D = Darcy Friction Factor (online tool)
ρ = Fluid Density [kg/m³]
v = Fluid Velocity [m/s]
D = Hydraulic Diameter [m] = 4 x Area / Perimeter

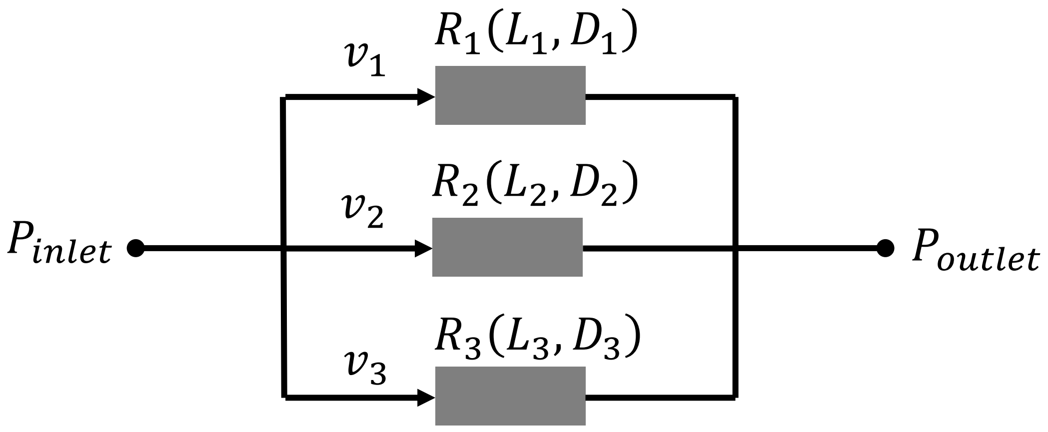
Step #1: Fluid Velocity Calculation

Assuming that there is a laminar flow (because of simplicity in calculation):

$$f_D = \frac{64}{Re} = \frac{64}{\left(\frac{v \cdot D}{\nu_{kin}}\right)}$$

where, Re = Reynolds Number
ν_{kin} = Kinematic Viscosity [m²/s]

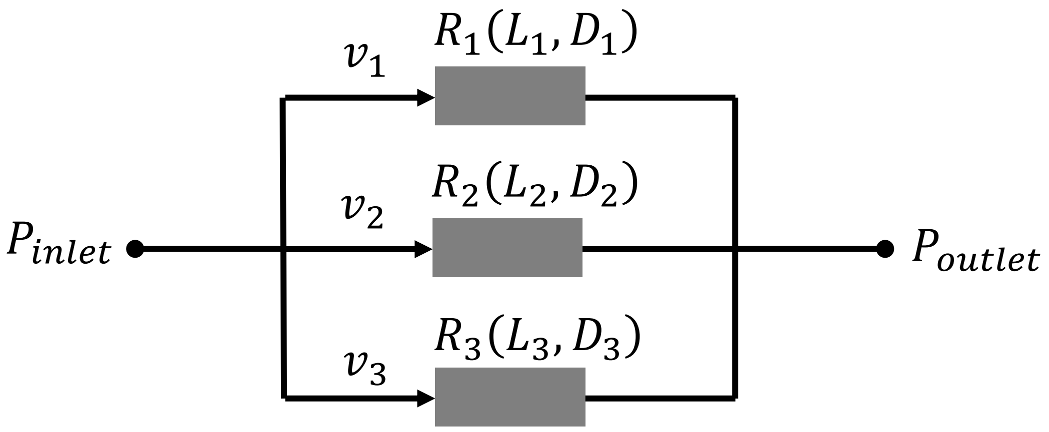
$$\Rightarrow \frac{\Delta P}{L} = 32 \cdot \frac{\rho \cdot \nu_{kin} \cdot v}{D^2}$$



Since for a given fluid type and flow, the pressure-drop per unit length will be same in all three finned channels,

$$\Rightarrow \frac{v}{D^2} = \text{Constant} \qquad \Rightarrow \left(\frac{v}{D^2}\right)_1 = \left(\frac{v}{D^2}\right)_2 = \left(\frac{v}{D^2}\right)_3$$

So, knowing the geometry of the individual channels (i.e., in terms of the hydraulic diameter) gives the information of the flow distribution amongst them.



For a given inlet volumetric flow rate into the cooling plate ($\dot{V}$),

$$\dot{V} = \frac{\dot{m}}{\rho} = \dot{V}_1 + \dot{V}_2 + \dot{V}_3 = (v_1 \cdot A_1) + (v_2 \cdot A_2) + (v_3 \cdot A_3)$$

$$\Rightarrow v_2 = \frac{\frac{\dot{m}}{\rho}}{\left(\frac{v_1}{v_2} \cdot A_1\right) + A_2 + \left(\frac{v_3}{v_2} \cdot A_3\right)} = \frac{\frac{\dot{m}}{\rho}}{\left(\frac{D_1{}^2}{D_2{}^2} \cdot A_1\right) + A_2 + \left(\frac{D_3{}^2}{D_2{}^2} \cdot A_3\right)}$$

And similarly, v_1 and v_3 is calculated.
Pressure-drop will obviously remain the same in every channel.

Step #2: Darcy Friction Factor Calculation

$$f_D = \begin{cases} \frac{64}{Re}, & \text{Laminar Flow } (Re \leq 2100) \\ \frac{1.352}{\left[\ln\left(\frac{e}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)\right]^2}, & \text{Turbulent Flow} \end{cases}$$

where, e = Surface Roughness [m]

Step #3: Pressure Drop Calculation

Put the flow velocity and the Friction Factor back in the Darcy-Weisbach Eqn:

$$\frac{\Delta P}{L} = f_D \cdot \frac{\rho}{2} \cdot \frac{v^2}{D}$$

Words of Caution – Real numbers WILL be higher.

- ***Calculation of the velocity distribution is done by assuming laminar flow for the sake of simplicity.***
- ***Pressure drop is calculated for straight tubes and having multiple turns will increase the pressure drop.***

[2] Theoretical Modelling – Thermal Aspects

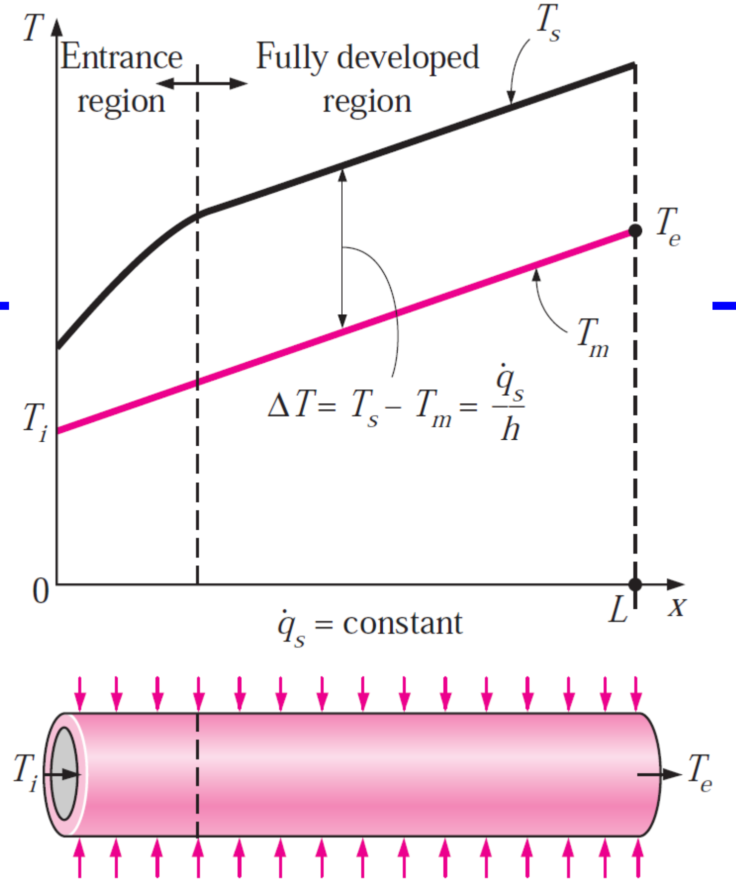
<u>Motivation</u> – How much flow at what temp. is required to cool away the electronics power dissipation and obtain the required temp. on the surface of the cooling plates (and consequently on the electronics)?

The cooling capacity ($\dot{Q}$) i.e., the power which we want to remove for a given flow and in a certain geometry is given by the following formulation, where the surface temp. on the cooling channels is our eventual observable:

$$\dot{Q} = h \cdot A_s \cdot (T_s - T_m)$$

$$\boxed{\Rightarrow T_s = T_m + \frac{\dot{Q}}{h \cdot A_s}}$$

where,
- **h = Heat Transfer Coefficient [W/m².K]**
- **A_s = Surface Area of the channel [m²]**
- **T_s = Channel's Surface Temp. [K]**
- **T_m = Fluid's Mean Temp. [K]**



Step #1: Fluid's Mean Temp. Calculation

The fluid's mean temp. can be calculated by:

$$T_m = \frac{T_i + T_e}{2}$$

where,
- **T_i = Inlet Temp. [K]**
- **T_e = Exit Temp. [K]**

Exit Temp. can be calculated by the fact that how much heat is absorbed the fluid:

$$\dot{Q} = \dot{m} \cdot C_p \cdot (T_e - T_i)$$

$$\Rightarrow T_e = T_i + \frac{\dot{Q}}{\dot{m} \cdot C_p}$$

where,
- **$\dot{m}$ = Mass Flow [kg/s]**
- **C_p = Specific Heat Capacity [J/kg.K]**

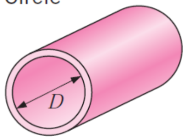
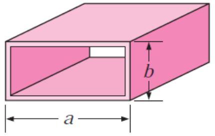
Theoretical Modelling – Thermal Aspects

Step #2: Heat Transfer Co-efficient Calculation

Heat Transfer Coefficient is calculated by:

$$h = \frac{Nu \cdot k}{D}$$

where, Nu = Nusselt Number
k = Thermal Conductivity [W/m.K]
D = Hydraulic Diameter [m]

Tube Geometry	a/b or θ°	Nusselt Number	
		T_s = Const.	$\dot{q}_s$ = Const.
Circle 	—	3.66	4.36
Rectangle 	a/b		
	1	2.98	3.61
	2	3.39	4.12
	3	3.96	4.79
	4	4.44	5.33
	6	5.14	6.05
	8	5.60	6.49
	∞	7.54	8.24

For a fully developed flow, the Nusselt Number is:

$$Nu = \begin{cases} 4.36, & \text{Laminar Flow (Circular Tube)} (Re \leq 4000) \\ 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}, & \text{Turbulent Flow} \end{cases}$$

where, Re = Reynold Number
Pr = Prandtl Number

Step #3: Average Surface Temp. Calculation

So, for the required cooling capacity ($\dot{Q}$), mass flow and cooling channel geometry, simply insert the values of the mean fluid temp. and the heat transfer co-efficient to obtain the average temp. on the top of the C-Frame:

$$\Rightarrow T_s = T_m + \frac{\dot{Q}}{h \cdot A_s}$$

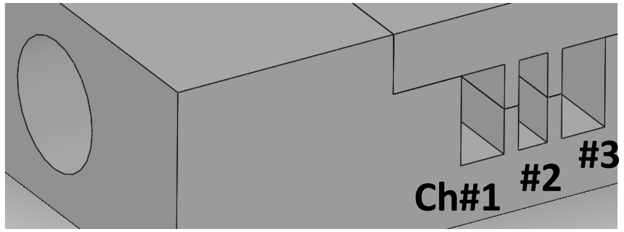
Words of Caution – Only the average temp. on the surface

- ***A constant power distribution is assumed over the tube. So, no hot-spots can be identified.***
- ***The Nusselt number is assumed for circular channels.***
- ***The Nusselt number is assumed for a fully developed flow (i.e., no entrance region calculated)***

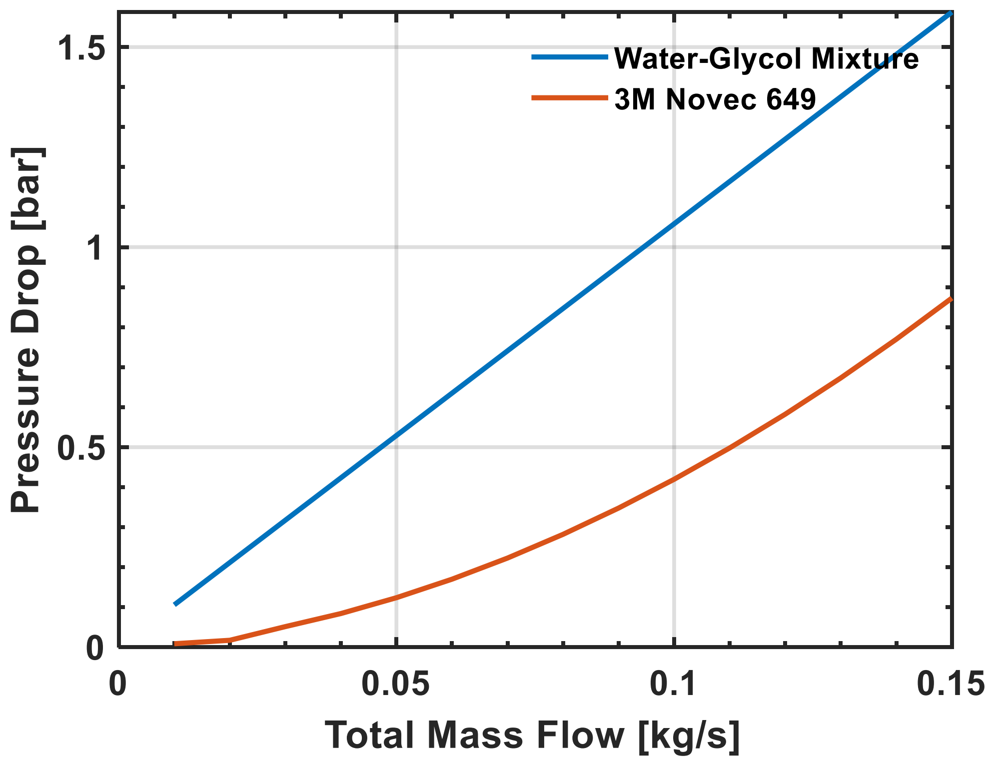
Some Predictions (With 01L Geometry)

Channel Geometry (based on the CAD file given) :

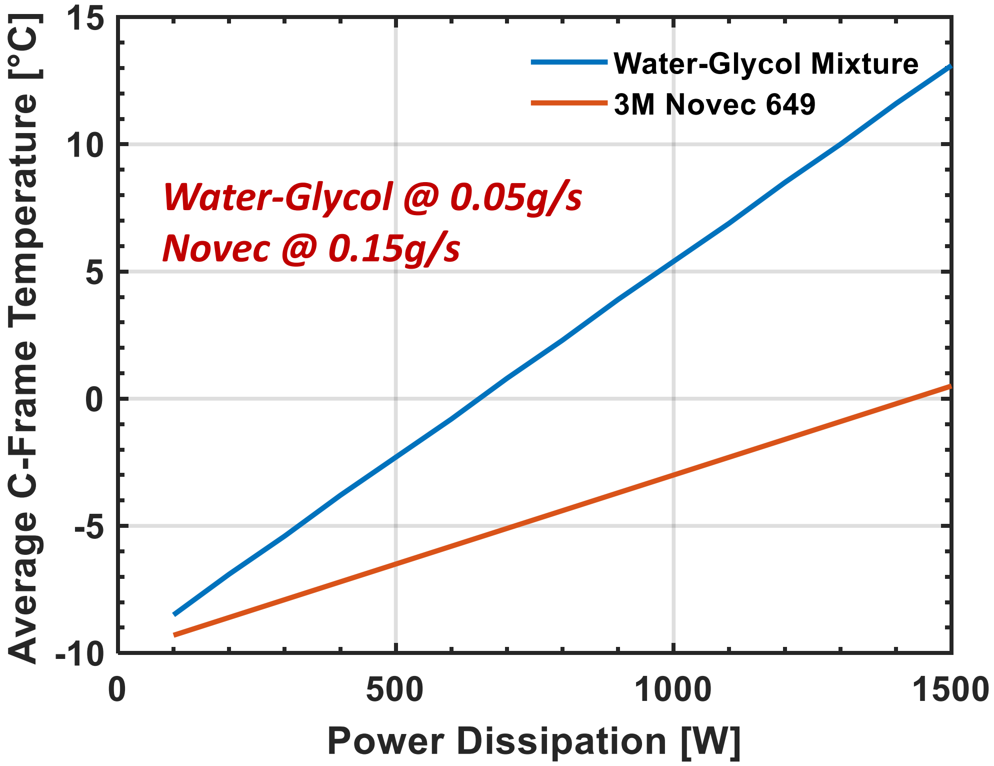
- **Ch#1: 3 x 6 mm² Ch#2: 2 x 6 mm² Ch#3: 3 x 6 mm²**
- **Length: 2.9 m (straight channels; w/o any turns or bends)**



Assuming the pressure drop limit of < 1 bar, Novec would allow for much higher mass flow due to its low viscosity



At lower power dissipation, both coolants are comparable. But Novec outperforms for higher power dissipation.

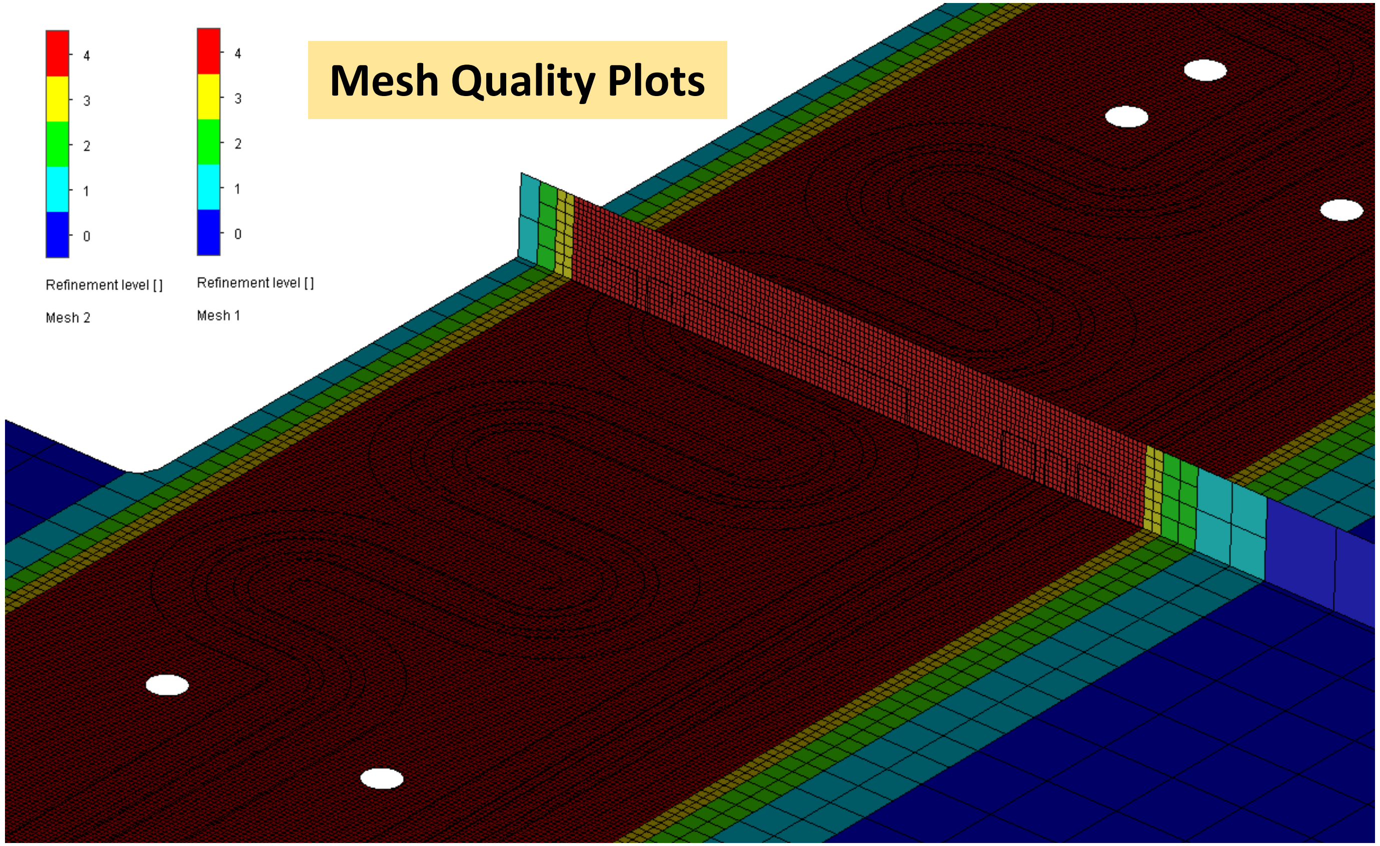


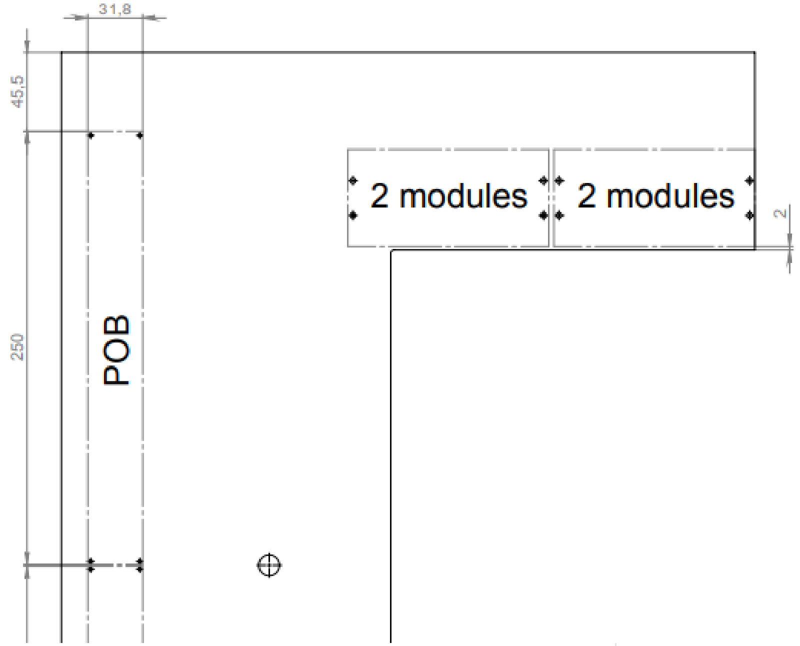
SolidWorks Computational Fluid Dynamics (CFD) Simulations

Simulation Inputs – C-Frame 01L

Total Power Dissipation (no ROBs???):

16 modules (32 FEBs) → **320W from FEBs (ASICs + LDOs; 10W/FEB)**
→ **96W from FEASTs (3W/FEAST-pair/FEB)**



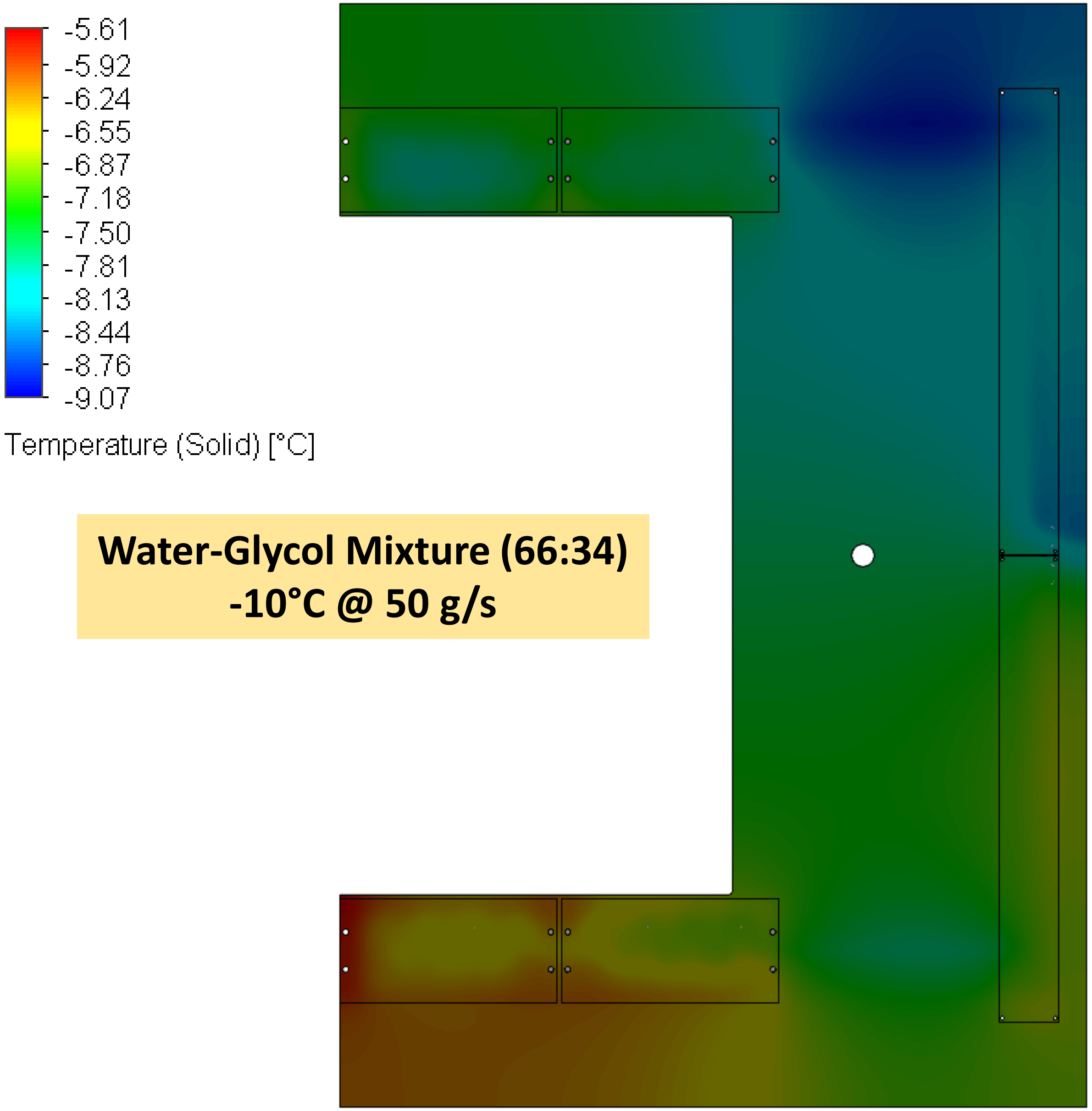


Parameter	Value
Status	Solver is finished.
Total cells	6,827,571
Fluid cells	1,160,212
Solid cells	5,667,359
Fluid cells contacting solids	439,022
Iterations	1,115
Last iteration finished	09:47:24
CPU time per last iteration	00:00:45
Travels	3.07087
Iterations per 1 travel	364
Cpu time	13 : 7 : 30
Calculation time left	0 : 0 : 0
Run at	DESKTOP-TIEEQ5V
Number of cores	4

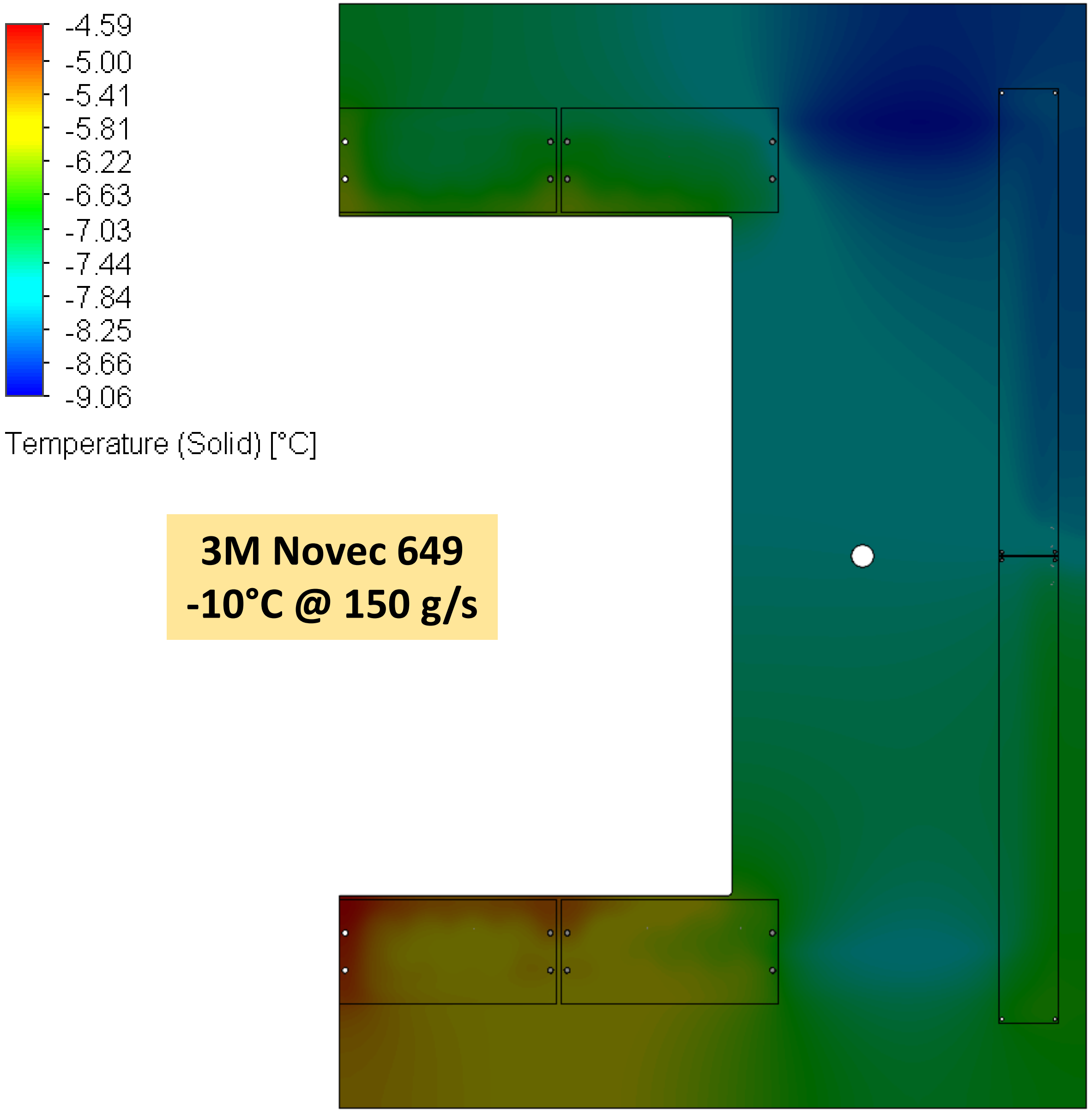
Computationally Intensive!!!

Results: Temperature Distribution

Nothing much separate the two fluids for 01L



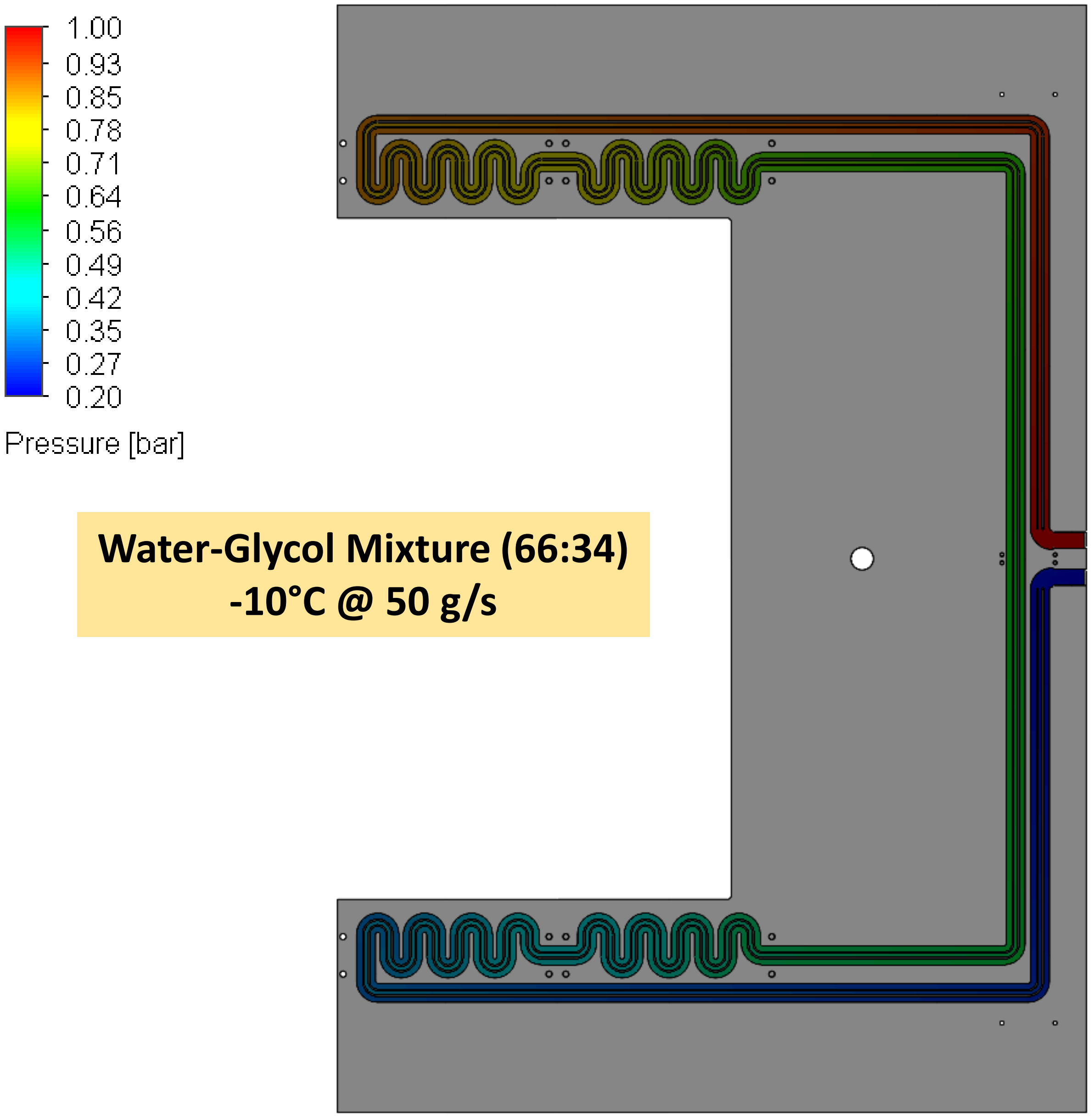
Water-Glycol Mixture (66:34)
-10°C @ 50 g/s



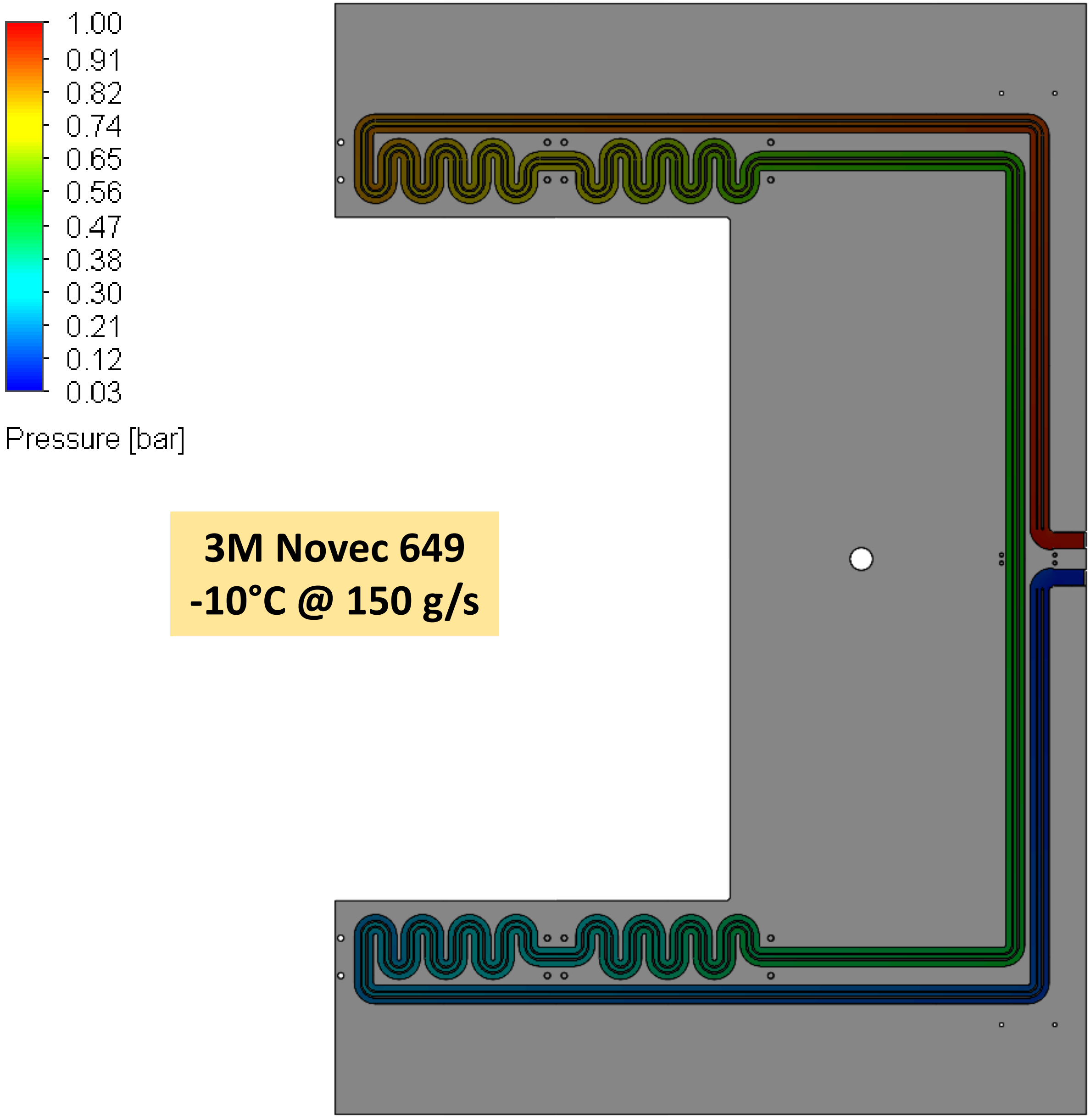
3M Novec 649
-10°C @ 150 g/s

Results: Pressure Distribution

Nothing much separate the two fluids for 01L



Water-Glycol Mixture (66:34)
-10°C @ 50 g/s

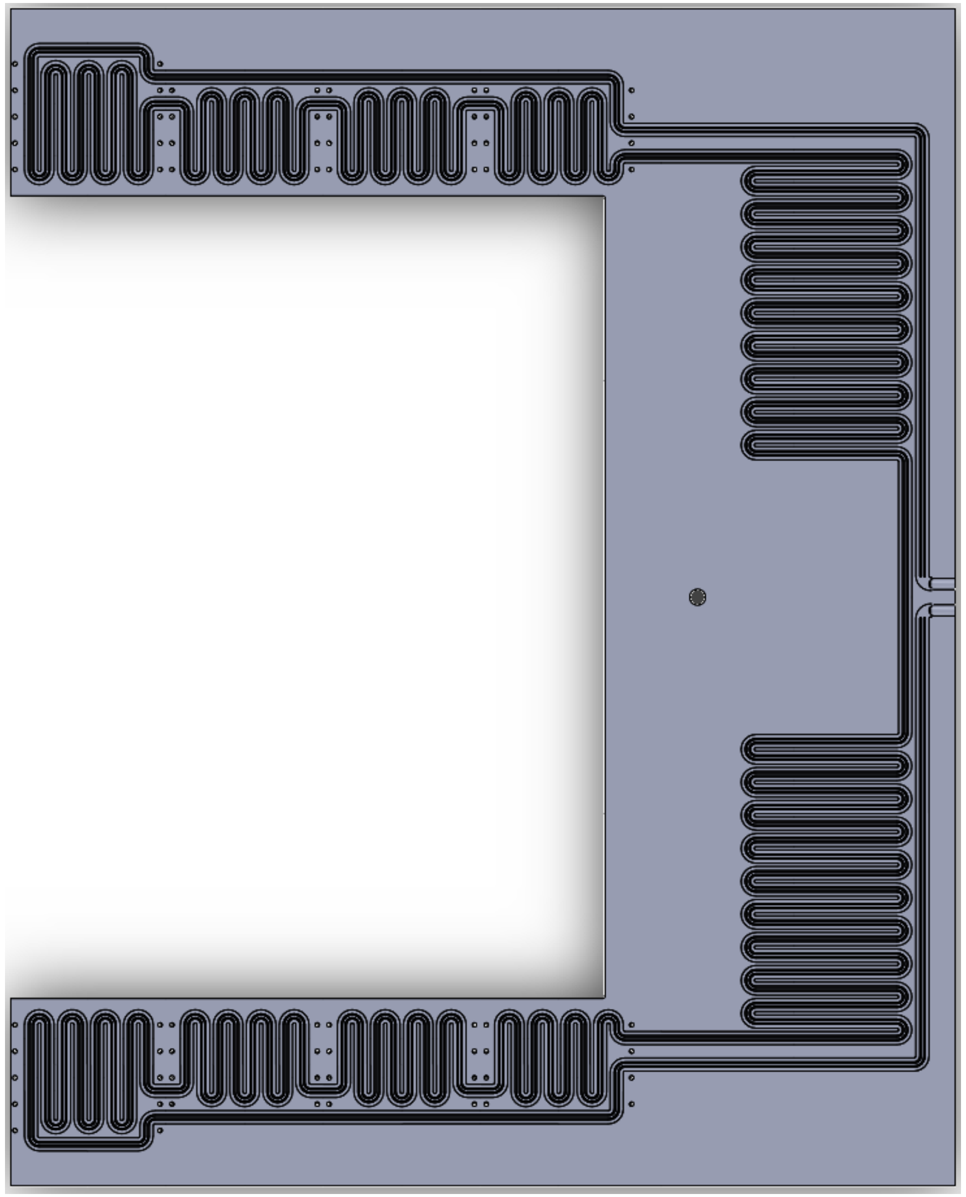


3M Novec 649
-10°C @ 150 g/s

Possible Next Steps

Possible Next Steps

- **My conclusion – 3M Novec 649 at -10°C should be the baseline option for BM@N-STS FEE cooling**
- **Studying the worse-case scenario can tell something conclusive, which is useful for constraining the boundary conditions for the cooling plant**
- **Close collaboration with C-Frame/Cooling Plate manufacturer must be established before any design freeze**
  - **CoolTec Electronic GmbH is a potential partner**
  - **Positive experience of CBM-STS**
  - **In-house capability to perform CFD and pressure-rating simulations**



Thanks A Lot ☺
Question/Comments/Suggestions?