

Design considerations for the 2-phase cooling system of a 5 MW MVDC converter

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ALSTOM

Nexans

EDF

| |
|---------------------------|
| Cooling system |
| Cooling fluids |
| Conclusion and references |

Application case: offshore wind turbine

[1]



Generating current in AC form and convert it to DC



Assemble all the currents from all wind turbines in DC form and deliver it over the sea



Convert the DC to AC current and connect it to the grid

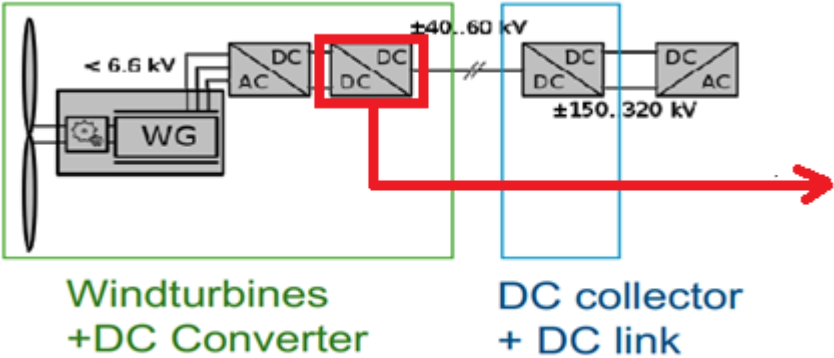
Project description

Cooling system

Cooling fluids

Conclusion and references

Project description : electronics



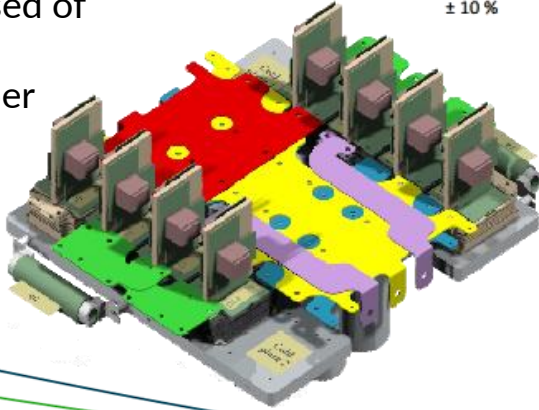
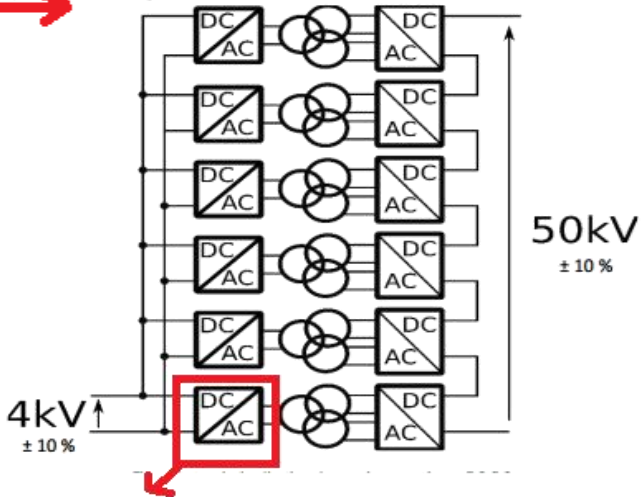
Converter (5MW)

Diagram

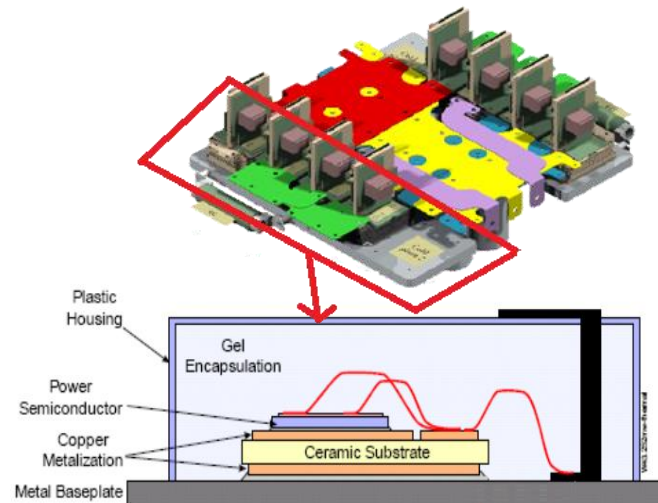
- IPOS : input parallel, output series
- 6 medium frequency transformers

Overview

- 12 inverters each composed of two half bridges
- 6 active power modules per inverter



Project description : electronics



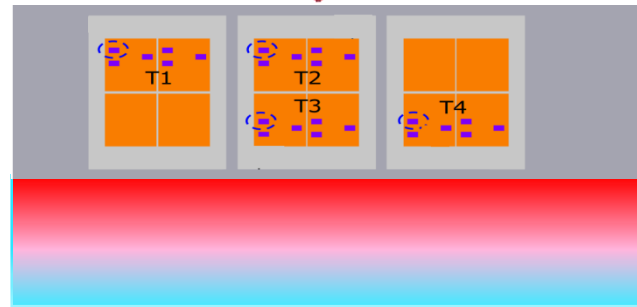
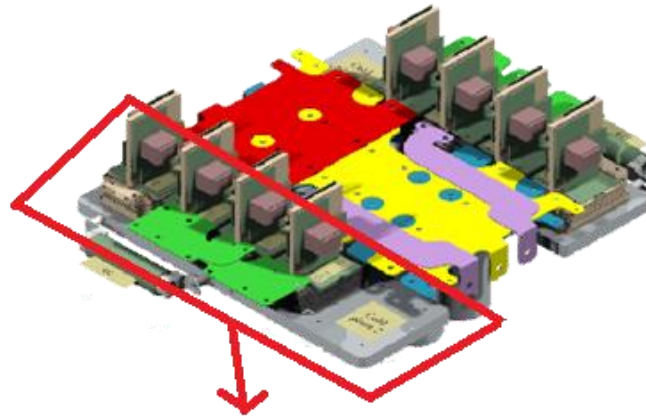
3 MOSFET modules per Half bridge

Half bridge properties :

- Target efficiency (**worst case**): **99%** (98%)
- Total Thermal power to be dissipated (**worst case**): **50** (100) kW
- Power dissipated per half bridge (**worst case**): **1,8** (4) kW
- Leg area to be cooled: $400 \times 150 \text{ mm}^2 = 600 \text{ cm}^2$
- Target junction temperature: **100 °C**
- Target Baseplate temperature: **70 °C**
- Power dissipated per module (**worst case**): **600** (1330) W
- Heat flux on the baseplate (**worst case**): **4.3** (9) W cm⁻²

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← 3 Power module per leg

← Cooling system

← Air (quiescent or Wind)



- Ambient temperature range: [-40 °C , 40 °C]
- Average wind speed: 2 m s⁻¹
 - Heat exchange coefficient: 20 W m⁻²K⁻¹
- Minimum temperature difference between air and condenser surface: 10 °C

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Why biphasic cooling ?

Power to be dissipated **1 kW**

| | Water | Methanol |
|---------------------------------------|--------------|-----------------|
| ρ_l kg/m ³ | 958 | 764 |
| Diphasic | | |
| H_{lv} kJ/kg | 2250 | 1540 |
| Q_m kg/s | 4E-04 | 6E-04 |
| Q_{eq} l/h | 1.7 | 3.1 |
| Monophasic | | |
| C_p J/(kg.K) | 4184 | 2620 |
| Q_m kg/s (for a $\Delta T = 50$ °C) | 5E-03 | 8E-03 |
| Q_{eq} l/h | 18.0 | 36.0 |

- Volume is up to **10 times less** in Biphasic cooling
- Biphasic cooling can be **passive**
- Biphasic cooling can be (almost) **isothermal**

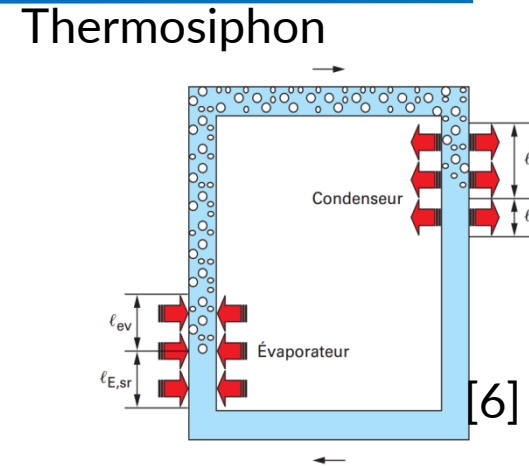
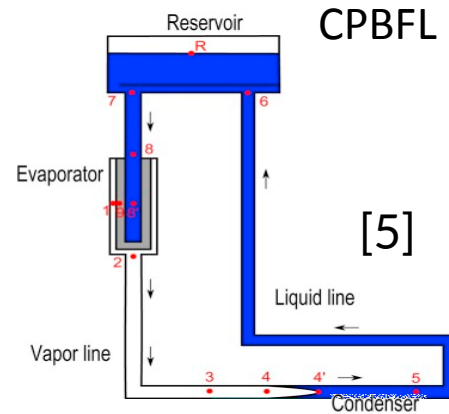
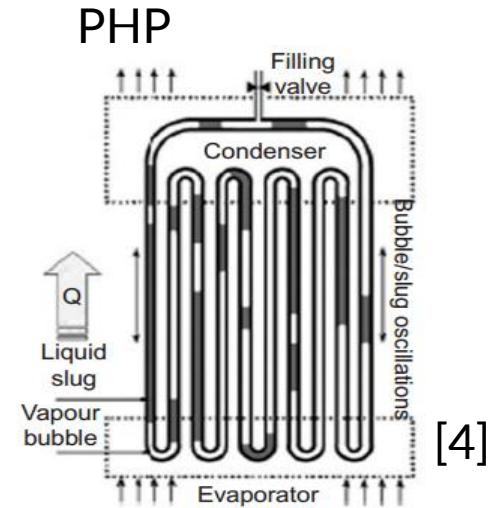
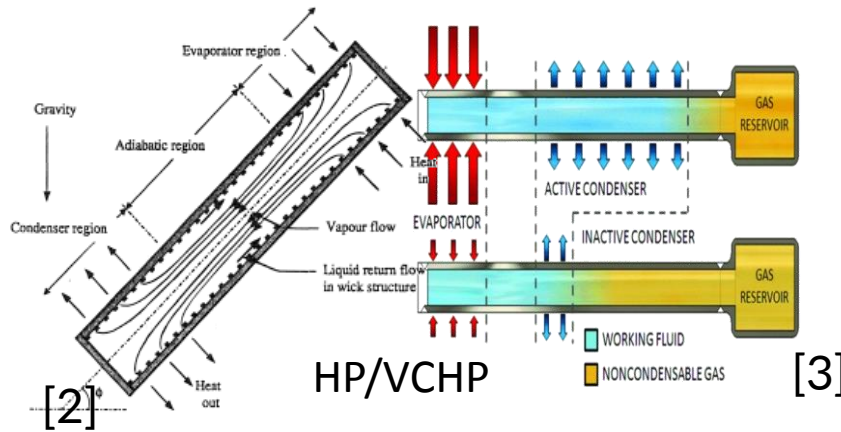
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Passive Cooling systems



| | Heat pipe | VCHP | Thermosiphon | PHP | CPBFL |
|------------------------|---------------|----------------|----------------|--------------|-----------------|
| Flow engine | σ/g | σ/g | $\Delta\rho$ | $\Delta\rho$ | σ |
| Regulation possibility | X | ✓ | X | X | ✓ |
| Power | 1 W m-100 W m | 10 W m-10 kW m | 10 W m-10 kW m | ? | 10 W m-1000 W m |

Cooling liquids : constraints

► Constraints on the fluid

- **No ozone depletion effect**
- **Small GWP(<150)**
- **Non flammable**
- **Harmless for short and long use (preferably 0 in the HMIS scale)**
- **Stable under temperature variation with material in use**
- **Freezing temperature <-40 °C**
- **Critical temperature >140 °C**
- **Acceptable Thermodynamic performances near atmospheric pressure**



NFPA rating label by SafetySign.com

Does not meet requirements

Missing Thermodynamic Data

[7]

ULP : Under low pressure

// UHP: Under high pressure

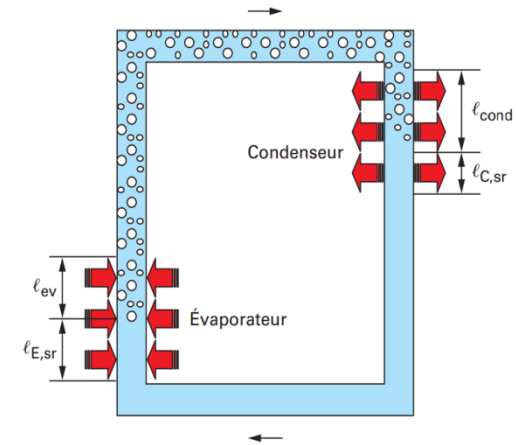
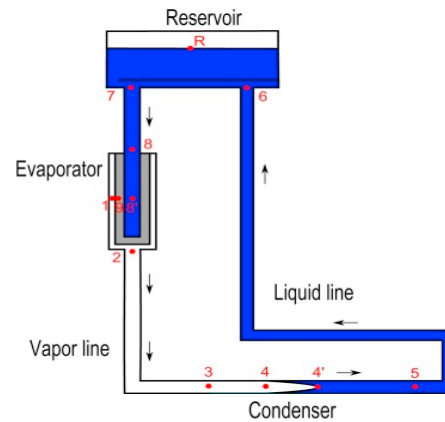
//F : flammability score

//H : Health score

| | Formula | M (g/mol) | Bp °C | Fp °C | ρl kg/m ³ | ρv kg/m ³ | Hv(kJ/kg) | Cpl | Kl (W/(m K)) | σ mN/m | μl (cP) | μv (cP) | F | AT °C | R | H | GWP | LT(years) | |
|-----|-------------------------|----------------|-------|-------|----------------------|----------------------|-----------|--------|--------------|--------|---------|----------|----------|-------|------|---|-----|-----------|--------|
| F,H | Ethanol | C2H6O1 | 46.0 | 78.0 | -114.0 | 0.789 | 1.60 | 836.0 | 2.78 | 0.171 | 19.2 | 4.02E-01 | 1.00E-02 | 3 | 419 | 0 | 2 | | |
| F | l-Propanol | C3H8O1 | 60.0 | 82.0 | -88.0 | 0.786 | 2.07 | 664.6 | 2.36 | 0.147 | 21.7 | 6.40E-01 | 9.00E-03 | 3 | 425 | 0 | 1 | | |
| F | Methanol | C1H4O1 | 32.0 | 64.0 | -98.0 | 0.792 | 1.11 | 1105.3 | 2.60 | 0.200 | 19.3 | 3.22E-01 | 1.10E-02 | 3 | 470 | 0 | 1 | | |
| F | 2-Propanol | C3H8O1 | 60.0 | 82.6 | -89.0 | 0.786 | 2.08 | 732.2 | 3.15 | 0.150 | 21.7 | 5.00E-01 | 9.30E-03 | 3 | 399 | 0 | 1 | | |
| F | n-Pentane | C5H12 | 72.0 | 36.0 | -129.0 | 0.626 | 2.50 | 355.3 | 2.50 | 0.098 | 16.0 | 1.92E-01 | | 4 | 260 | 0 | 1 | | |
| F | n-Hexane | C6H14 | 86.0 | 69.0 | -95.0 | 0.659 | 2.99 | 334.4 | 2.40 | 0.110 | 18.4 | 2.02E-01 | | 3 | 225 | 0 | 1 | | |
| F,H | Benzene | C6H6 | 78.0 | 80.0 | 5.5 | 0.879 | 2.80 | 393.3 | 1.90 | 0.130 | 28.9 | 3.10E-01 | 9.30E-03 | 3 | 592 | 0 | 2 | | |
| F | Cyclohexane | C6H12 | 84.0 | 81.0 | 6.5 | 0.778 | 2.90 | 355.3 | 1.86 | 0.100 | 25.0 | 4.20E-01 | 8.00E-03 | 3 | 260 | 0 | 1 | | |
| F,H | Toluene | C7H8 | 92.0 | 110.6 | -95.0 | 0.867 | 3.20 | 362.8 | 1.81 | 0.132 | 23.5 | 2.50E-01 | 9.50E-03 | 3 | 480 | 0 | 2 | | |
| F | Acetone | C3H6O1 | 58.0 | 56.0 | -95.0 | 0.790 | 2.00 | 510.0 | 2.29 | 0.168 | 23.3 | 3.30E-01 | 9.00E-03 | 3 | 465 | 0 | 1 | | |
| F | methyl ethyl ketone | C4H8O1 | 72.0 | 80.0 | -87.0 | 0.805 | 2.50 | 455.6 | 2.19 | 0.160 | 24.6 | 2.35E-01 | | 3 | 485 | 0 | 1 | | |
| F | methyl acetate | C3H6O2 | 74.0 | 57.0 | -98.0 | 0.927 | 2.57 | 403.8 | 2.09 | 0.144 | 23.0 | 2.50E-01 | | 3 | 500 | 0 | 1 | | |
| F | Ethyl acetate | C4H8O2 | 88.0 | 77.0 | -84.0 | 0.895 | 3.04 | 367.8 | 2.03 | 0.130 | 24.0 | 2.57E-01 | 9.00E-03 | 3 | 484 | 0 | 1 | | |
| F | isopropyl acetate | C5H10O2 | 102.0 | 89.0 | -69.0 | 0.874 | 3.50 | 338.6 | 1.93 | 0.134 | 22.1 | 4.60E-01 | | 3 | 460 | 0 | 1 | | |
| F,H | Carbon tetrachloride | C1Cl4 | 154.0 | 76.0 | -23.0 | 1.580 | 5.34 | 196.5 | 0.83 | 0.096 | 27.0 | 4.56E-01 | 1.15E-02 | 0 | none | 0 | 3 | | |
| F,H | 1,2-Dichloroethane | C2H4Cl2 | 99.0 | 83.5 | -36.0 | 1.235 | 3.40 | 321.9 | 1.29 | 0.700 | 32.2 | 4.26E-01 | | 3 | 413 | 0 | 3 | | |
| F,H | Trichloroethane | C2H3Cl3 | 133.0 | 74.0 | -30.0 | 1.338 | 4.62 | 244.5 | 1.13 | 0.096 | 30.0 | 6.50E-01 | | 1 | 537 | 0 | 2 | | |
| F,H | Methylene Chloride | C1H2Cl2 | 85.0 | 40.0 | -95.0 | 1.392 | 2.95 | 330.2 | 1.52 | 0.130 | 28.1 | 4.40E-01 | 1.20E-02 | 1 | 605 | 0 | 2 | | |
| F,H | Tetrahydrofuran | C4H8O1 | 72.0 | 66.0 | -109.0 | 0.888 | 2.50 | 386.9 | 1.71 | 0.120 | 28.0 | 5.50E-01 | | 3 | 212 | 1 | 2 | | |
| F,H | Methyl tert butyl ether | C5H12O1 | 88.0 | 55.0 | -109.0 | 0.741 | 3.06 | 333.9 | 2.14 | 0.112 | 18.3 | 3.50E-01 | | 3 | 460 | 0 | 1 | | |
| F,H | Diisopropyl ether | C6H14O1 | 102.2 | 68.5 | -60.0 | 0.725 | 3.58 | 283.7 | 2.13 | 0.116 | 18.0 | 3.30E-01 | | 3 | 430 | 1 | 1 | | |
| F,H | Diethyl ether | C4H10O1 | 74.0 | 34.5 | -116.0 | 0.715 | 2.57 | 351.1 | 2.32 | 0.137 | 17.0 | 1.96E-01 | | 4 | 160 | 1 | 2 | | |
| Fp | Water | H2O | 18.0 | 100.0 | 0.0 | 0.958 | 0.63 | 2253.3 | 4.21 | 0.685 | 72.3 | 8.90E-01 | 1.10E-02 | 0 | 0 | 0 | 0 | | |
| Fp | Water ULP (0.2bar) | H2O | 18.0 | 60.0 | 0.0 | 0.983 | 0.13 | 2385.4 | 4.18 | 0.653 | 66.7 | 4.60E-01 | 1.05E-02 | 0 | 0 | 0 | 0 | | |
| F,H | Acetonitrile | C2H3N1 | 41.0 | 81.6 | -44.0 | 0.782 | 1.42 | 727.3 | 2.23 | 0.154 | 29.1 | 3.00E-01 | | 3 | 524 | 0 | 2 | | |
| F,H | Carbon disulfide | C1S2 | 76.0 | 46.0 | -111.0 | 1.260 | 2.70 | 355.3 | 1.05 | 0.160 | 32.0 | 3.60E-01 | 1.05E-02 | 4 | 102 | 0 | 3 | | |
| H | Bromine | Br2 | 159.9 | 58.8 | -7.9 | 3.103 | 5.50 | 187.4 | 1.29 | 0.122 | 41.0 | 7.20E-01 | 1.70E-02 | 0 | none | 0 | 3 | | |
| GWP | R-134a UHP 16.8bar | CH2FCF3 | 102.3 | 60.0 | -103.0 | 1.060 | 80.00 | 134.0 | 1.28 | 0.018 | 3.7 | 1.24E-01 | 1.37E-02 | 0 | | 1 | 1 | 1300 | 140.00 |
| GWP | Novec 7100 | C4F9OCH3 | 250.0 | 61.0 | -135.0 | 1.510 | 9.00 | 112.0 | 1.18 | 0.069 | 13.6 | 5.80E-01 | 9.60E-03 | 0 | 0 | 0 | 3 | 297 | 4.00 |
| 1 | Novec 7200 | C4F9OC2H5 | 264.0 | 76.0 | -138.0 | 1.420 | 9.09 | 119.0 | 1.22 | 0.068 | 13.6 | 5.80E-01 | 9.60E-03 | 1 | | 0 | 3 | 59 | 0.77 |
| GWP | FC-3284 | | 299.0 | 50.0 | -73.0 | 1.710 | 11.13 | 105.0 | 1.11 | 0.062 | 13.0 | 5.50E-01 | | 0 | | 0 | 3 | 5000 | |
| GWP | FC-72 | C6F14 | 338.0 | 56.0 | -90.0 | 1.680 | 12.35 | 88.0 | 1.50 | 0.057 | 10.0 | 6.40E-01 | | 0 | none | 0 | 0 | 5000 | |
| GWP | Novec 649 | C3F5OCF(CF3) | 316.0 | 49.0 | -100.0 | 1.490 | 18.08 | 84.6 | 1.13 | 0.052 | 8.0 | 4.10E-01 | 1.26E-02 | 0 | 0 | 0 | 1 | 1 | 0.01 |
| GWP | Flutec PP2 ULP | C7F14 | 350.0 | 70.0 | -30.0 | 1.788 | 12.27 | 88.0 | 0.96 | 0.060 | 9.3 | 7.20E-01 | 1.22E-02 | 0 | 0 | 0 | 0 | 5000 | |
| F,H | HFO 1234yf UHP 16.4bar | CF3CF=CH2 | 114.0 | 60.0 | NA | 0.941 | 99.75 | 110.4 | 1.66 | 0.053 | 2.4 | 1.00E-01 | 1.48E-02 | 2 | | | 2 | 1 | |
| H | HFO rz 1233 UHP 4bar | (E)CF3-CH=CClH | 130.5 | 60.0 | -90.0 | 1.220 | 21.19 | 190.0 | 1.30 | 0.080 | 13.3 | 4.90E-01 | 1.24E-02 | 0 | 0 | 0 | 2 | 1 | 0.07 |
| F | HFO 1234ze UHP 13,3b | CF3CH=CHF | 114.0 | 60.0 | NA | 1.024 | 73.000 | 134.0 | 1.57 | 0.062 | 4.4 | 1.27E-01 | 1.40E-02 | 1 | | 0 | 1 | <1 | |
| F,H | HFE-7000 UHP 2.5bar | CF3CF2CF2OCH3 | 200.0 | 62.0 | -122.0 | 1.296 | 20.19 | 178.0 | 1.29 | 0.063 | 10.0 | 2.94E-01 | 1.20E-02 | 0 | 0 | 0 | 3 | 530 | 4.90 |
| F | H152 a UHP 15.6bar | CF2HCH3 | 66.0 | 62.0 | -117.0 | 0.793 | 50.00 | 226.0 | 2.07 | 0.082 | 5.0 | 1.06E-01 | 1.10E-02 | 4 | | 1 | 1 | 124 | |
| GWP | HFE 245fa2 UHP 3bar | CHF2OCH2CF3 | 150.0 | 62.0 | -82.0 | 1.280 | 17.91 | 165.2 | 1.40 | 0.060 | 11.0 | 2.79E-01 | 1.25E-02 | 0 | 0 | 0 | 2 | 812 | 5.66 |

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| Cooling fluids |
| Conclusion and references |

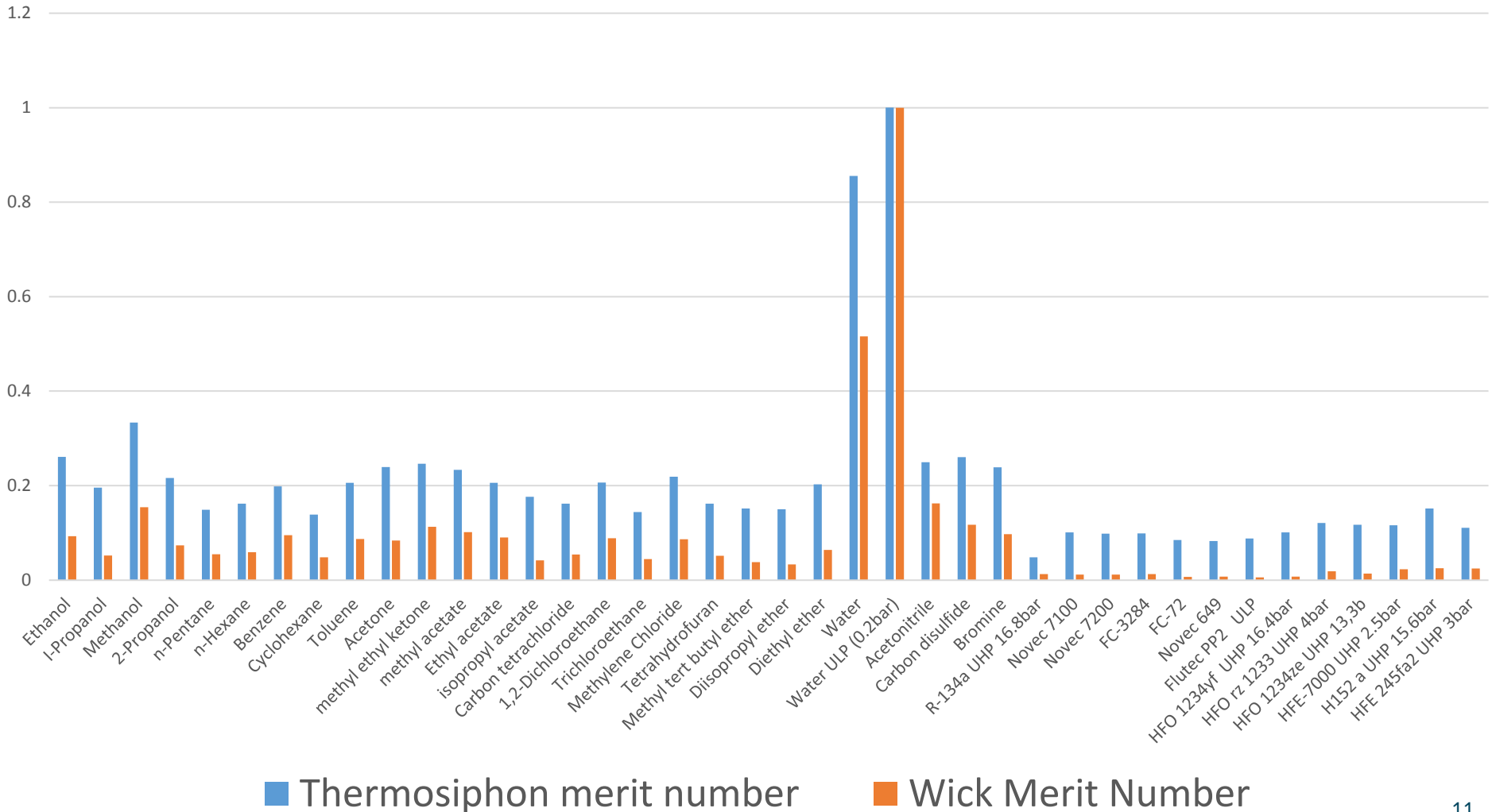
Merit numbers



| Region | Wick | Vapor line (turbulent friction) | Liquid line(gravity) | Condenser (laminar) | thermosiphon |
|-----------------|---|---|-------------------------|---|---|
| Merit Number | $\frac{\rho_l \sigma \cos\theta h_{lv}}{\mu_l}$ | $\frac{\sigma^4 h_{lv}^7 \rho_v^4 \cos\theta^4}{\mu_v}$ | $\frac{\sigma}{\rho_l}$ | $\frac{\sigma h_{lv} \rho_v \cos\theta}{\mu_v^{0.25} \mu_l^{0.75}}$ | $\left[\frac{k^3 h_{lv} \rho_l^2}{\mu_l} \right]^{0.25}$ |

Cooling Fluids : Merit numbers

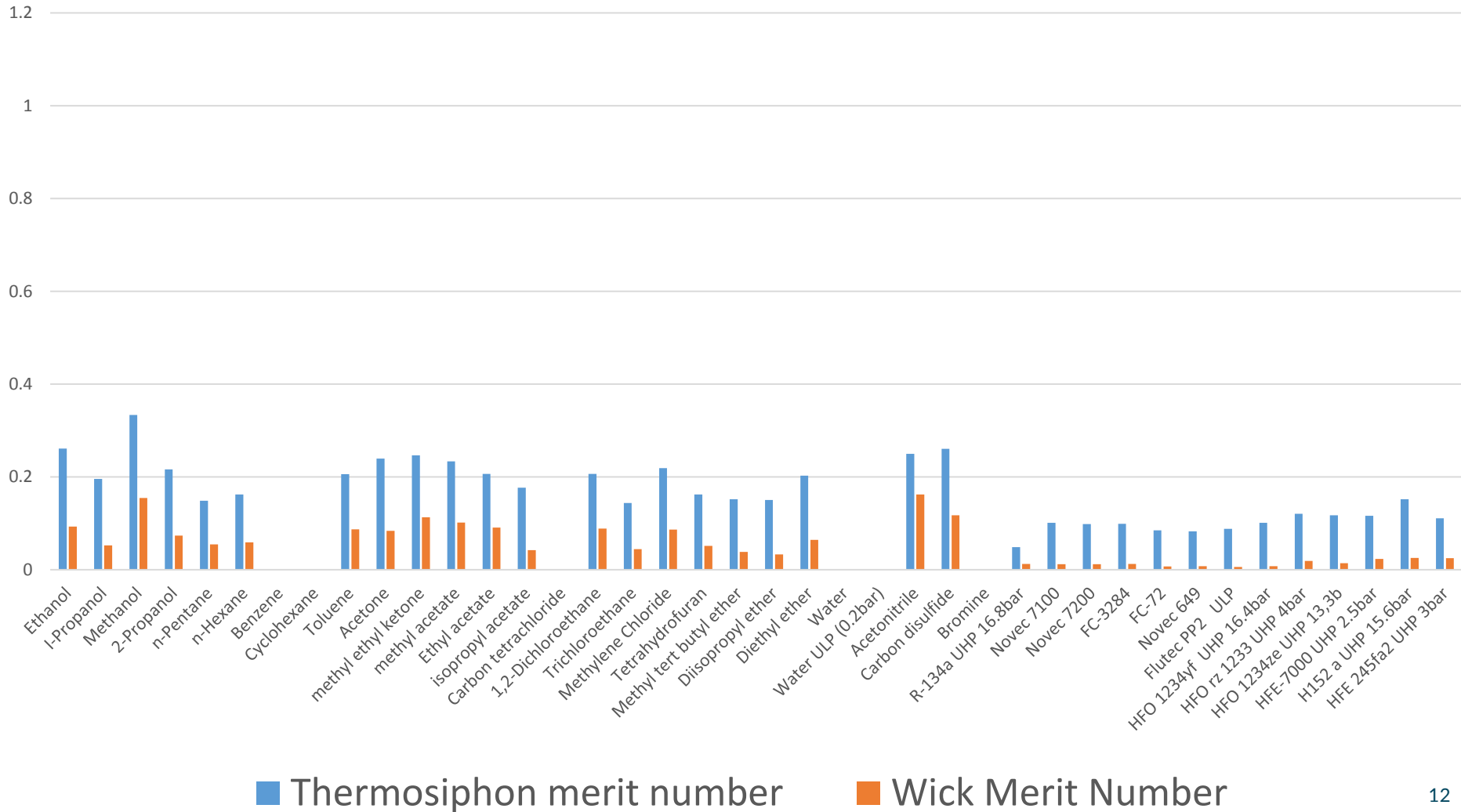
Merit Number comparison



Cooling Fluids : Merit numbers

~~Fp > -40°C~~

Merit Number comparison

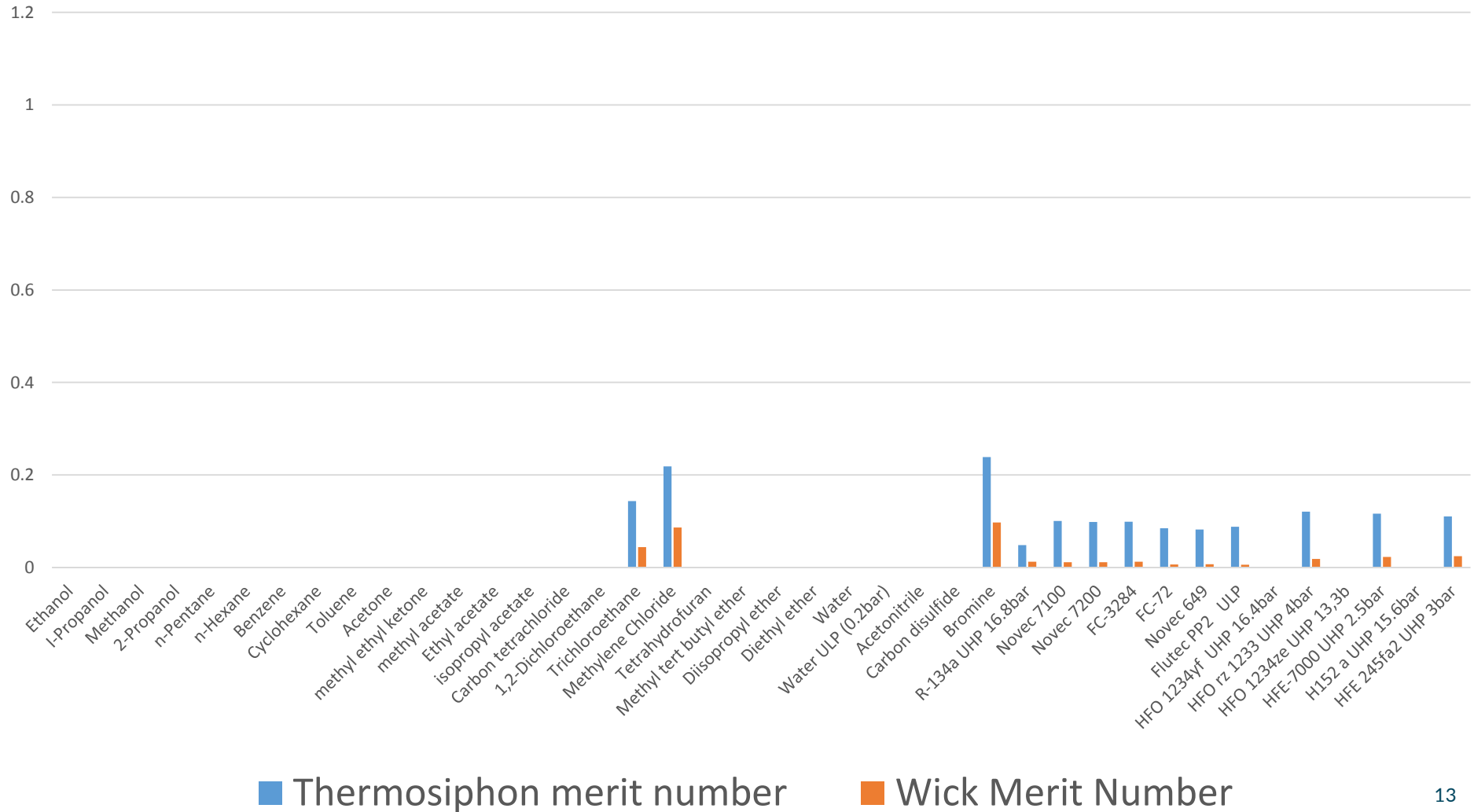


Cooling Fluids : Merit numbers

• ~~Fp > -30°C~~

• ~~Highly flammable~~

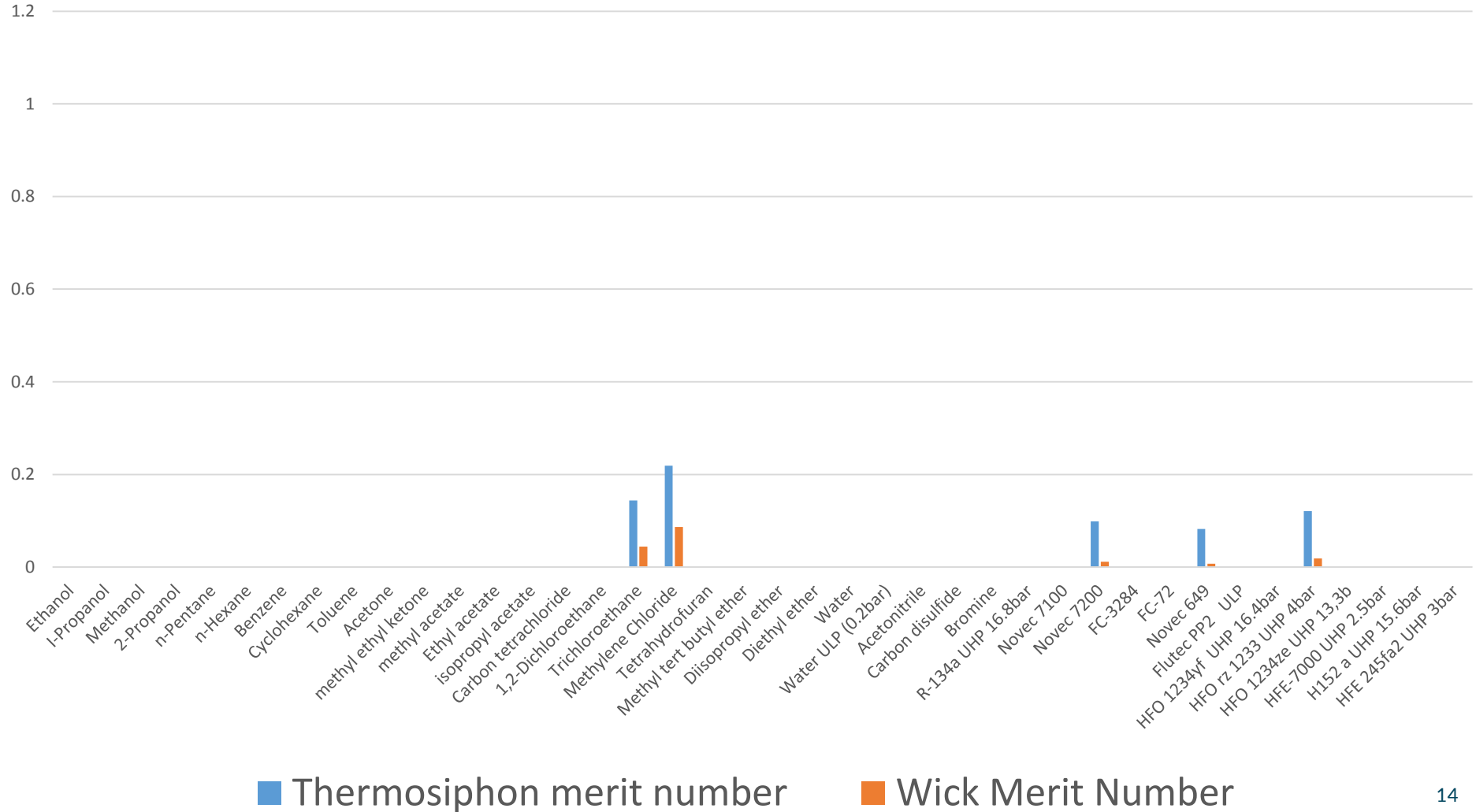
Merit Number comparison



Cooling Fluids : Merit numbers

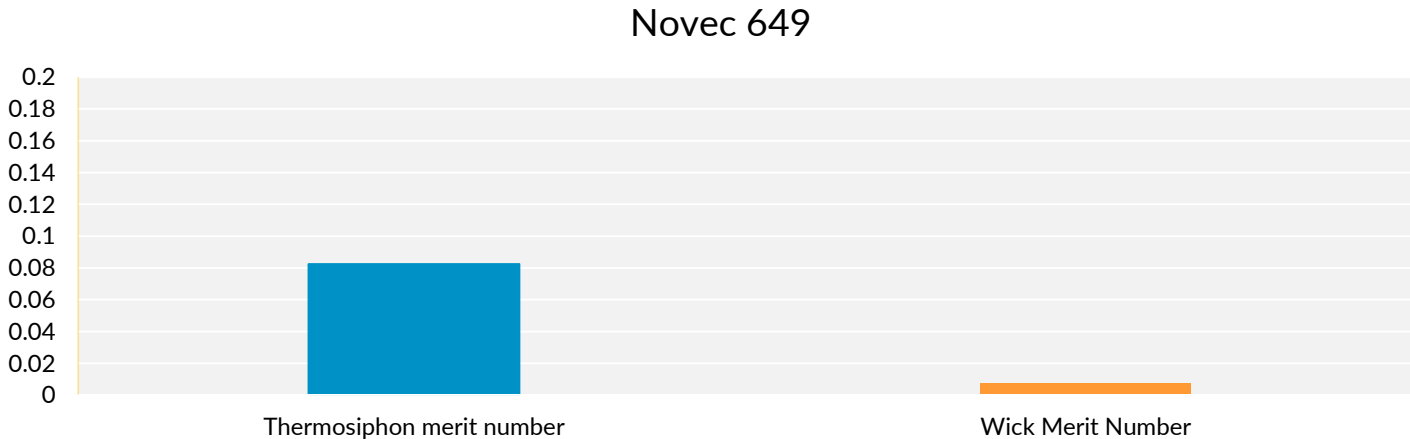
- ~~Fp > -30°C~~
- ~~Highly flammable~~
- ~~GWP > 150~~

Merit Number comparison



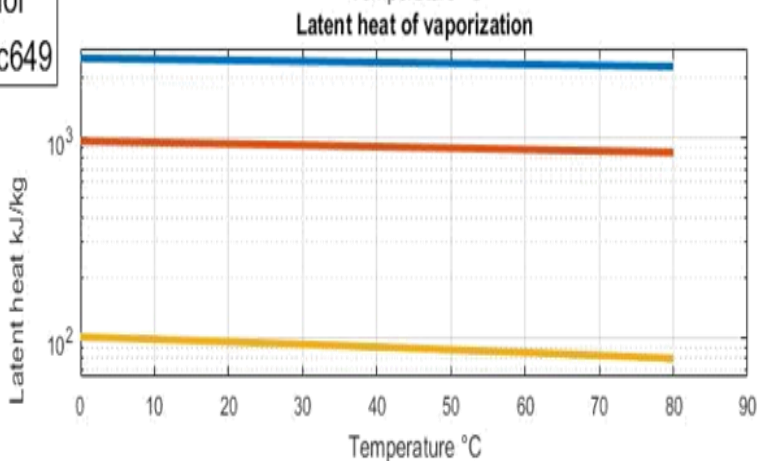
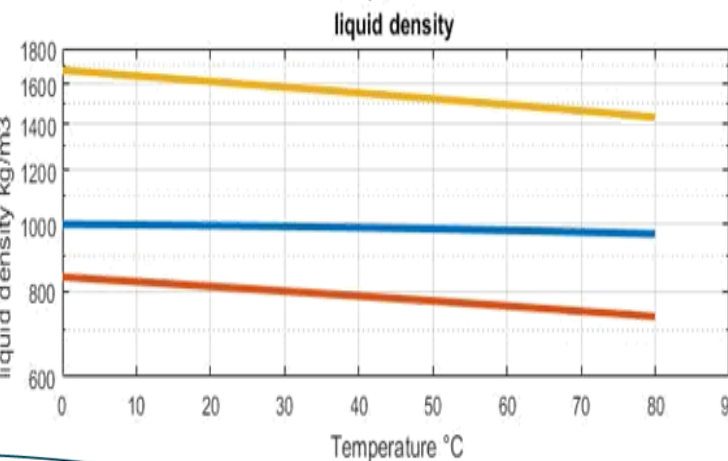
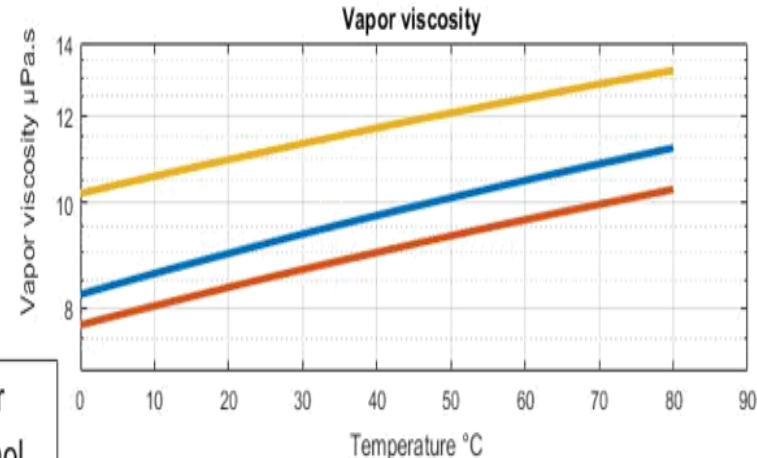
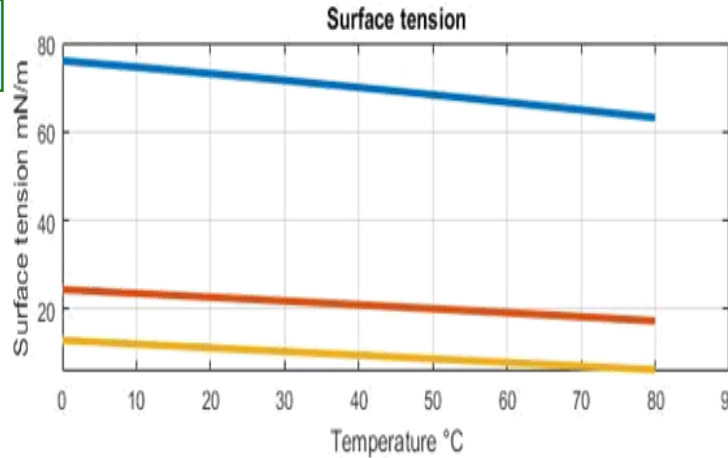
Cooling Fluids : Merit numbers

- ~~Fp > -30°C~~
- ~~Highly flammable~~
- ~~GWP > 150~~
- ~~Harmful fluids~~



Novec649: less than **8%** the merit number of water for a thermosiphon and **0.7%** that of a Capillary system

Limitations

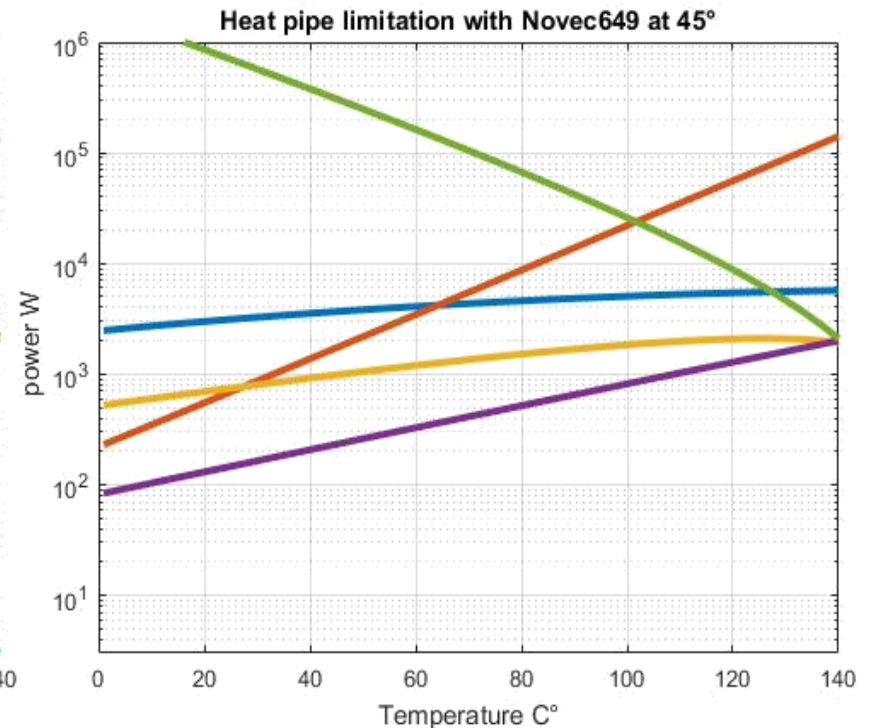
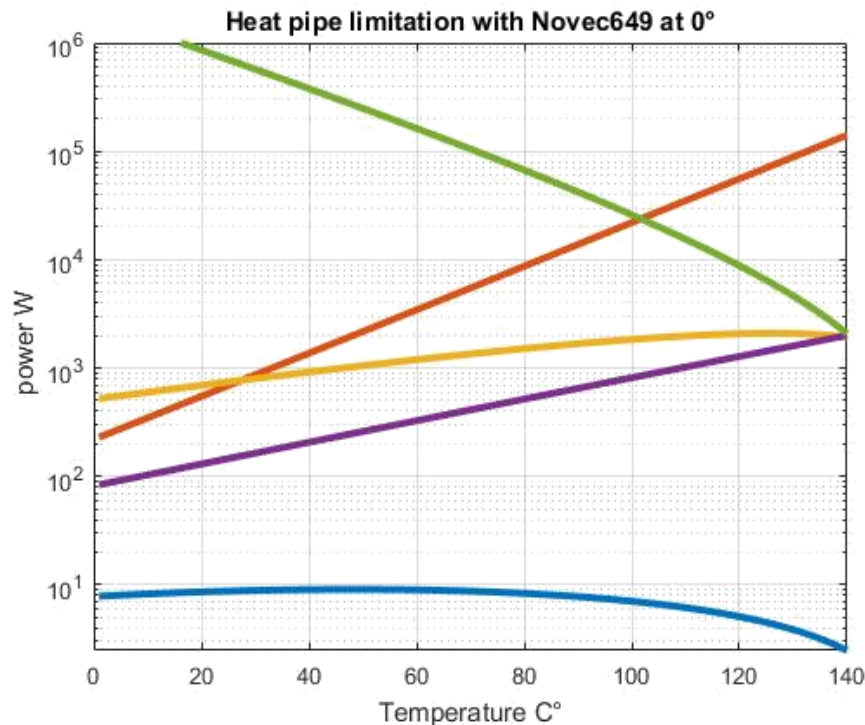
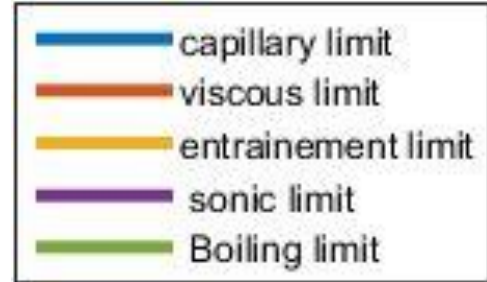


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Limitations : heat pipe

$\Phi_i=2.4\text{cm}$, $L=7\text{m}$

Power per heat pipe = 360W

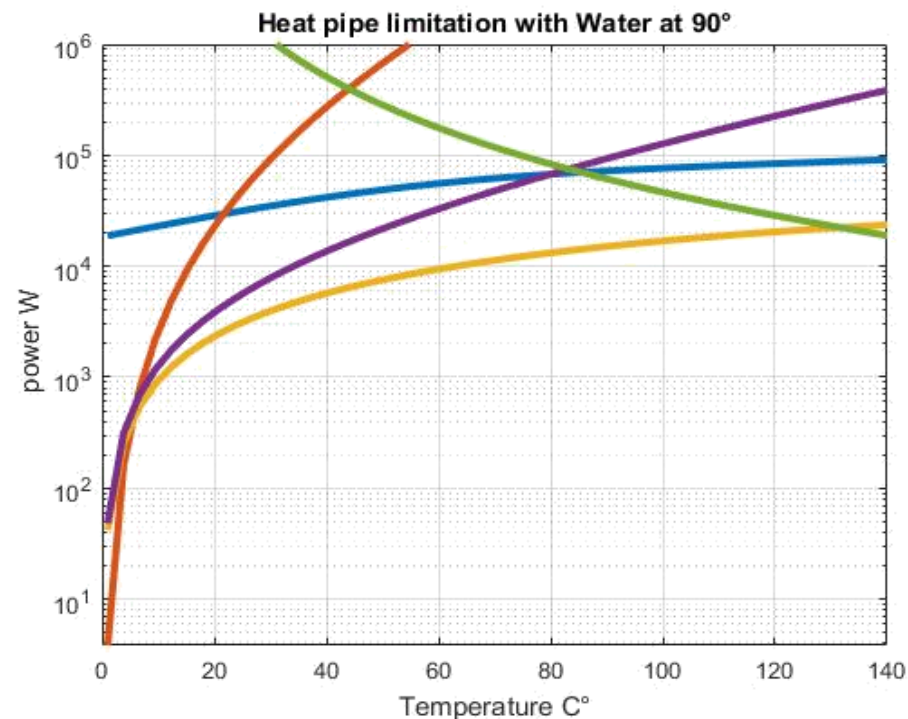
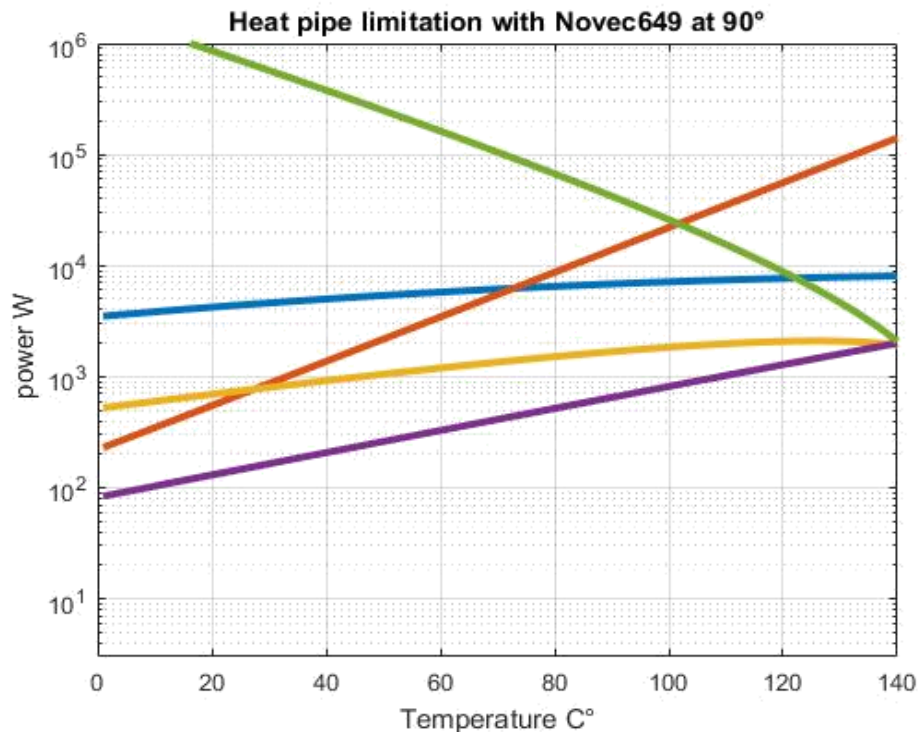
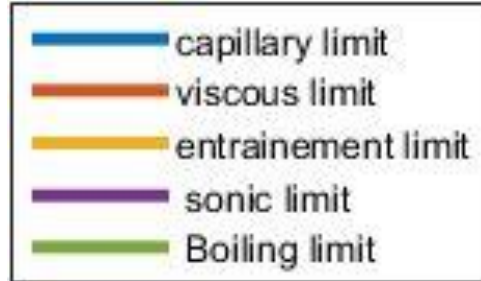


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Limitations : heat pipe

$\Phi_i = 2.4\text{cm}$

Power per heat pipe = 360W



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Conclusion and references

Conclusion

- Selection of the appropriate fluid depends on the system, **constraints were alone enough to limit the viable fluid to only one option: NOVEC 649** is the only fluid which meets (to a certain degree) all the requirements.
- Cooling system: Comparative calculations and power range point us to a **thermosiphon** despite a merit number **much lower** than water.
- Next step would be the **design and prototyping** of a thermosiphon with this working fluid

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References

- [1] : <https://www.ouest-france.fr/>
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 - https://fr.wikipedia.org/wiki/HVDC_Inter-Island
- [2] : <http://www.thermopedia.com/content/5257/HeaFF1.gif>
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- [7]: <https://www.honeywell.com/>
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Thank you

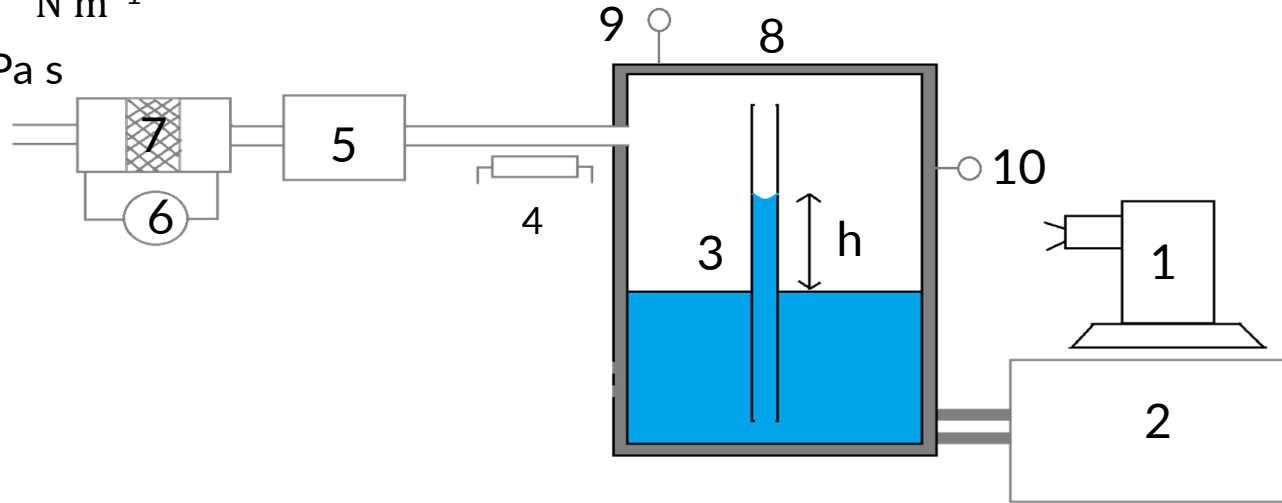


Bonus: How to calculate the Missing data

- Surface tension
- Dynamic viscosity
- Tsat & Psat

σ : N m^{-1}

μ_v : Pa s



- 1: Camera
- 2: Thermostat
- 3: Capillary tube
- 4: Heating resistance
- 5: Flow meter
- 6: manometer
- 7: porous media
- 8: Sealed and temperature controlled container filled with the fluid in biphasic state
- 9: Manometer
- 10: Thermometer

$$\sigma_{sat} = \frac{h \rho_{sat} g r}{2 \cos \theta}$$

$$\mu_v = \frac{\Delta p}{V k L}$$