WATER-EVAPORATION SUPPORTED FUEL CELL COOLING ARCHITECTURES FOR AIRCRAFT

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Acknowledgements

CLEAN AVIATION

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What is the fundamental issue?

$$\text{Payload} \xrightarrow{\textit{Structure}} \text{Weight} \xrightarrow{W = L} \text{Lift} \xrightarrow{\textit{Aerodynamics}} \text{Drag} \xrightarrow{D = T} \text{Thrust} \xrightarrow{\textit{Powertrain}} \text{Power} \xrightarrow{\textit{Propulsion System}} \text{Waste heat}$$

$$\frac{W_{\text{Payload}}}{W_{\text{MTOM}}} = 0.2 \ldots 0.4 \qquad \frac{L}{D} = 15 \ldots 20 \qquad \frac{P_{\text{Thrust}}}{P_{\text{FC}}} = 0.7 \ldots 0.8 \qquad \frac{\dot{Q}}{P_{\text{FC}}} \approx 1$$

25%

Conservation of Energy

Heat and Masstransfer

$$\frac{\dot{m}_{\text{air}}}{\dot{Q}} = 33 \frac{\text{kg/s}}{\text{MW}} \longleftarrow \dot{Q} = \dot{m}_{\text{air}} c_{p,\text{air}} (T_{\text{out}} - T_{\text{in}})$$

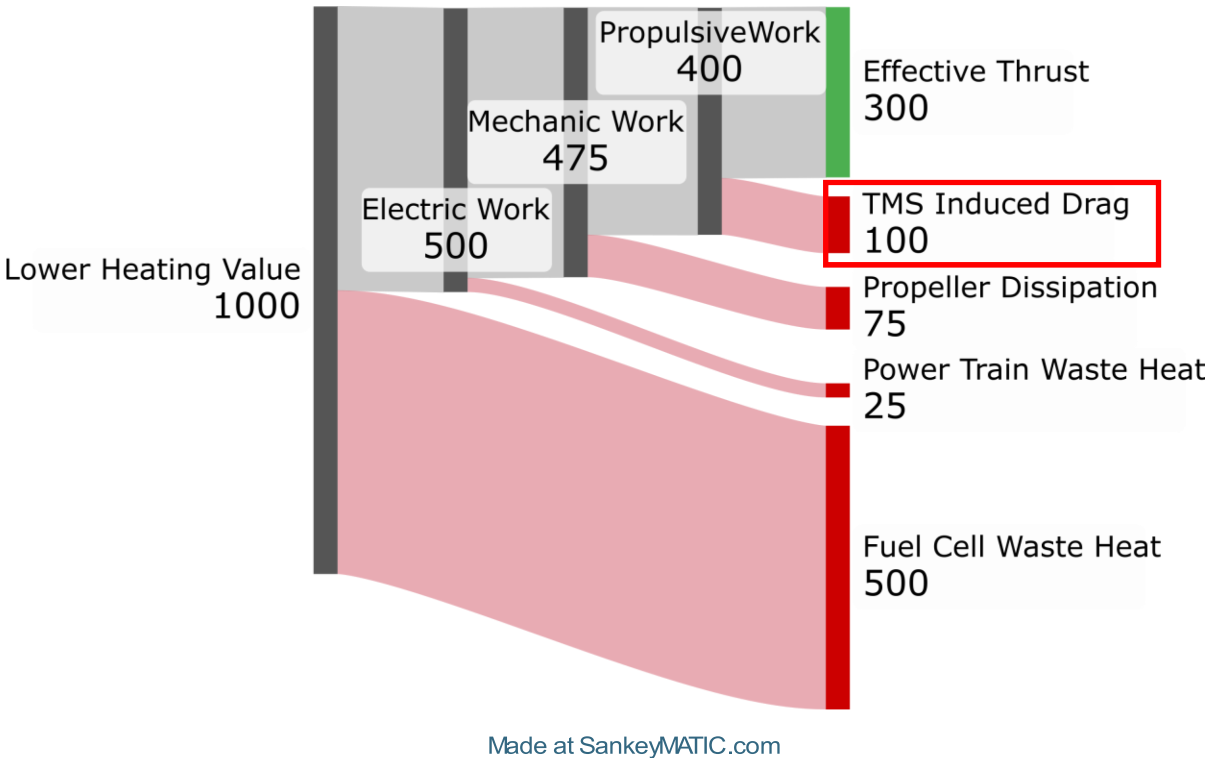
$$T_{\text{in}} = T_\infty = 50\,^\circ\text{C}$$

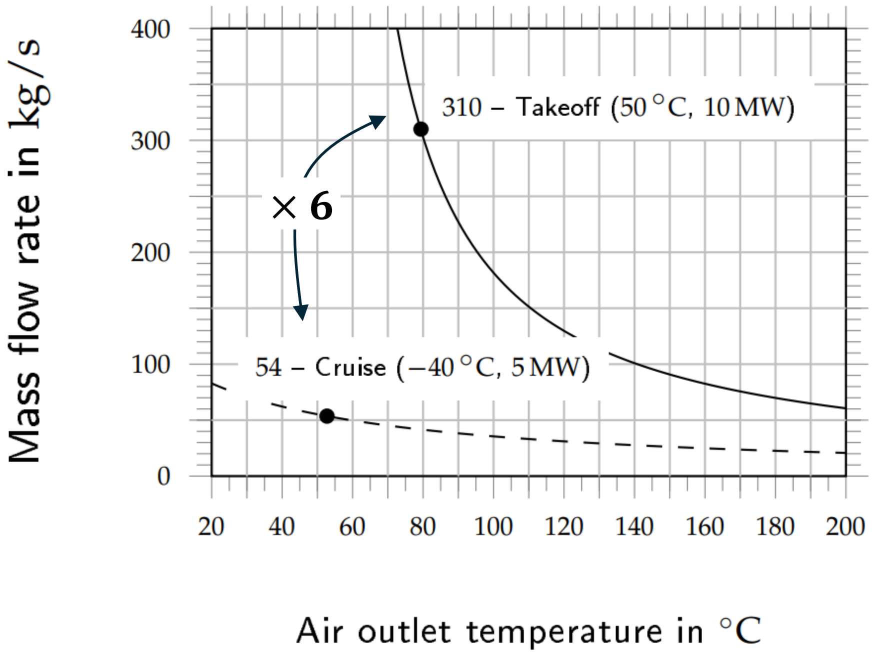
$$T_{\text{out}} = T_{\text{FC}} = 80\,^\circ\text{C}$$

$$\dot{Q} = 10\,\text{MW}$$

$$\dot{m}_{\text{air}} = 330 \frac{\text{kg}}{\text{s}} = 75\,\%\ \dot{m}_{1-\text{engine,A320}}$$

What is the fundamental issue?





Cooling system oversized

How do we usually cool?


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Image by ChNPP, via Wikimedia Commons, CC BY-SA 3.0

Why is water so beneficial?

$$\text{Payload} \xrightarrow{\textit{Structure}} \text{Weight} \longrightarrow \text{Lift} \xrightarrow{\textit{Aerodynamics}} \text{Drag} \longrightarrow \text{Thrust} \xrightarrow{\textit{Powertrain}} \text{Power} \xrightarrow{\textit{Propulsion System}} \text{Waste heat}$$

Conservation of Energy

Heat and Masstransfer

$$\dot{Q} = \dot{m}_{H_2O}\left(\underbrace{\Delta h_{evap}(T_0) + c_{p,v}(T_{out} - T_0)}_{h_{H_2O,out}} - \underbrace{c_l(T_{in} - T_0)}_{h_{H_2O,in}}\right)$$

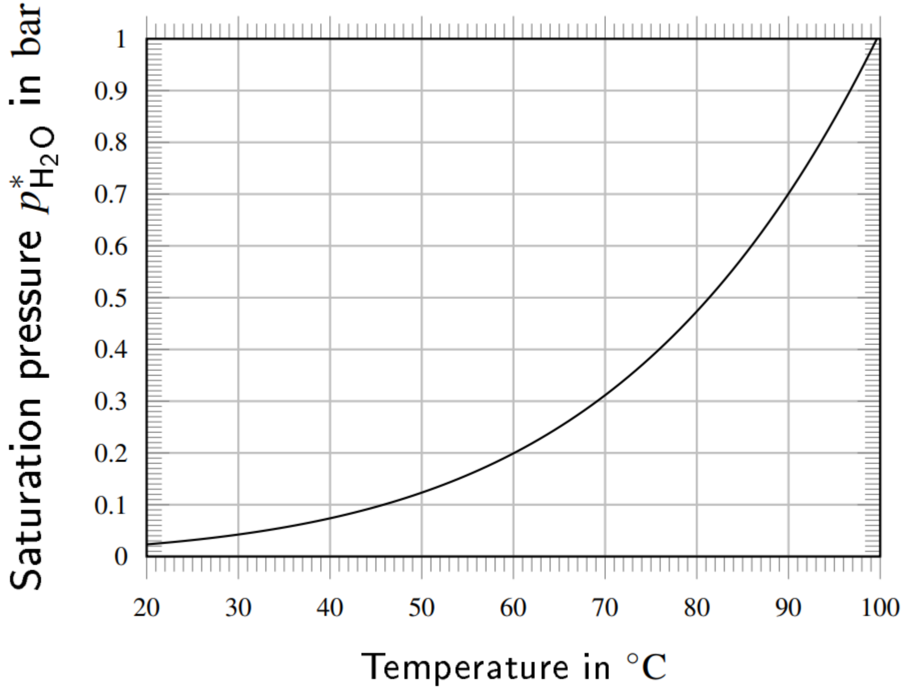
$$\frac{\dot{m}_{H_2O}}{\dot{Q}} = 0.41\,\frac{\mathrm{kg/s}}{\mathrm{MW}} = \frac{1}{80}\,\frac{\dot{m}_{air}}{\dot{Q}} \longleftrightarrow \frac{\dot{m}_{air}}{\dot{Q}} = 33\,\frac{\mathrm{kg/s}}{\mathrm{MW}}$$

$$m_{H_2O} = 610\,\mathrm{kg}$$

$$\dot{Q} = 10\,\mathrm{MW} \times 50\,\%$$

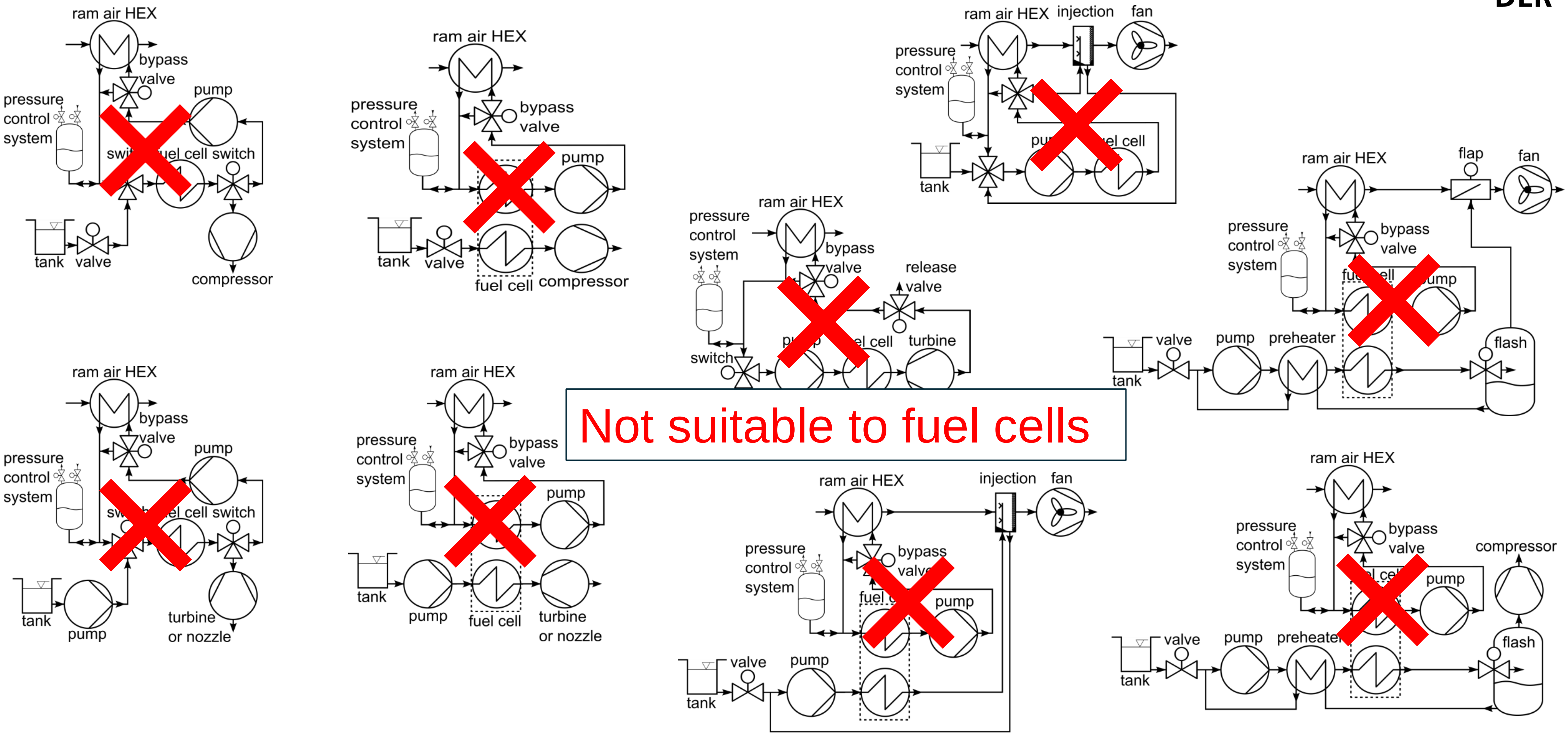
$$\Delta t = 5\,\mathrm{min}$$

The Engineering Task - develop an evaporation system



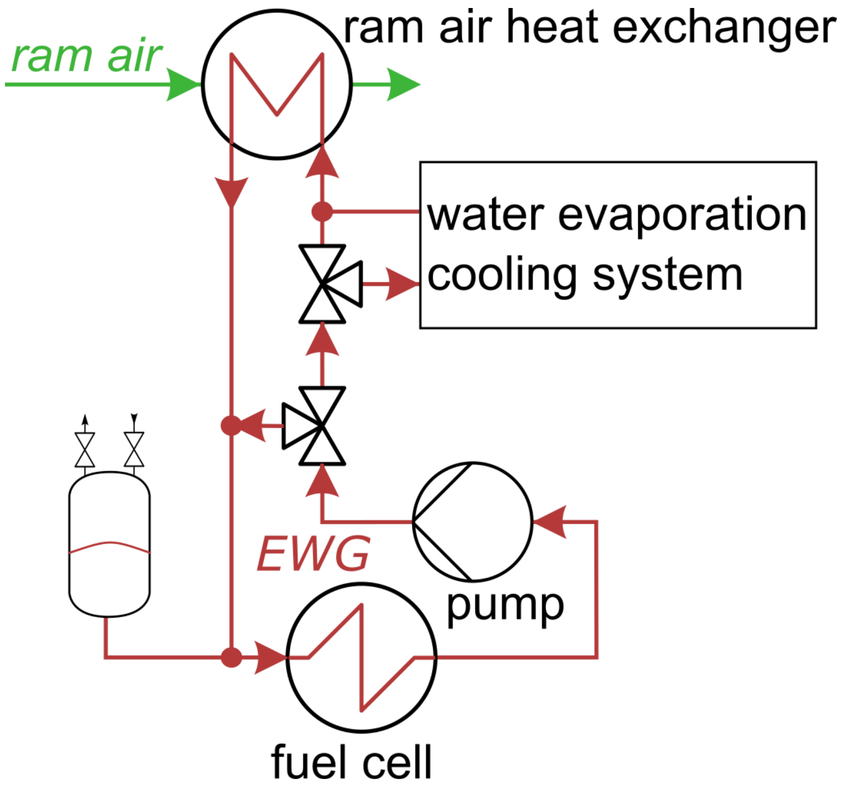
→Saturation vapor pressure curve of water

Multiple ideas – none approved by fuel cell experts



Not suitable to fuel cells

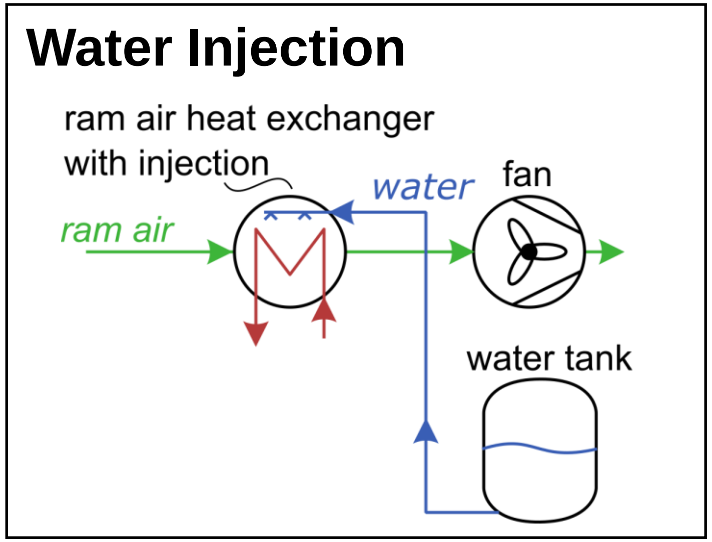
Conclusion – keep the conventional cooling loop

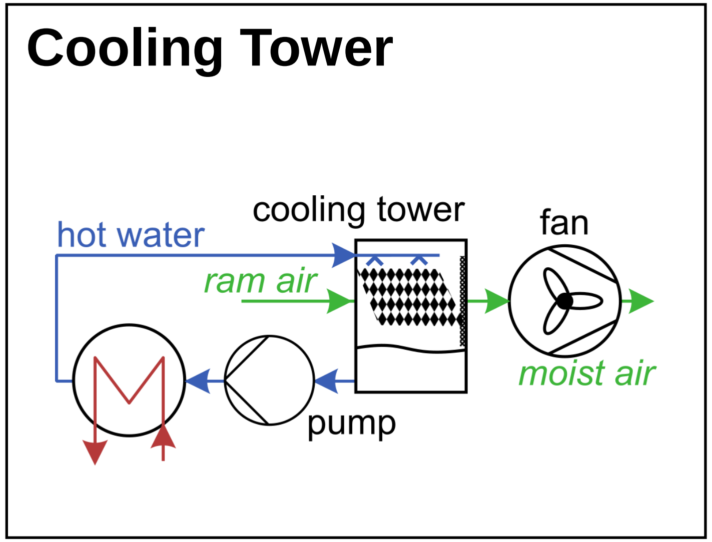


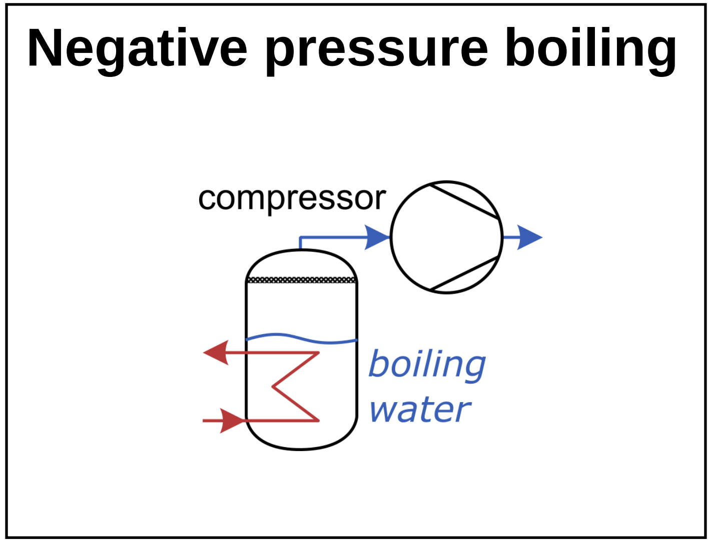
Hybrid cooling architecture

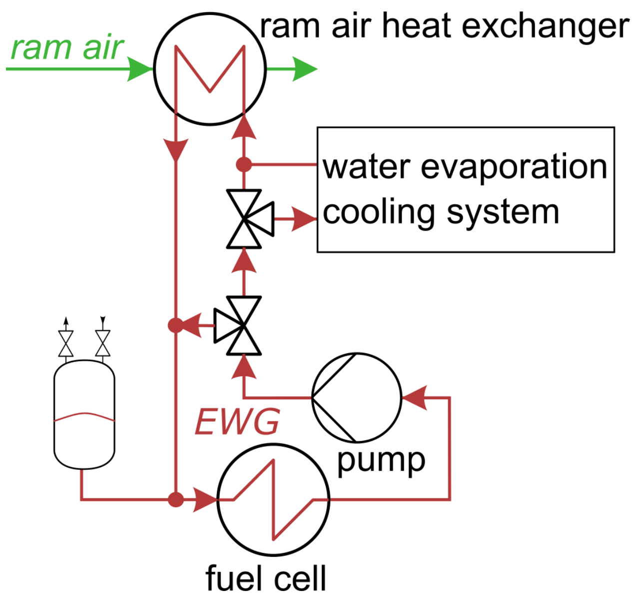
- Keep the conventional (e.g. liquid) cooling loop
  - Purity to meet fuel cell requirements
  - Limited electrical conductivity
  - Freeze-protection
- Ram-air cooling for normal operation, optimized for cruise
- Additional water evaporation cooling system for support during high cooling demand (e.g. takeoff at hot-day conditions)

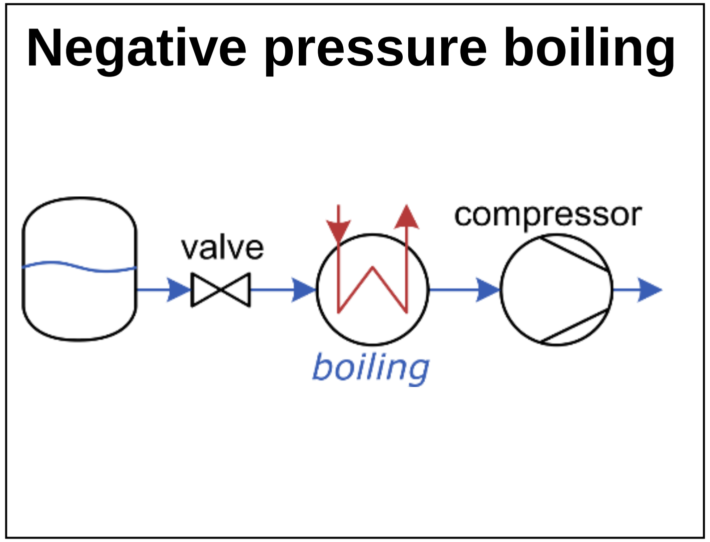
Concepts

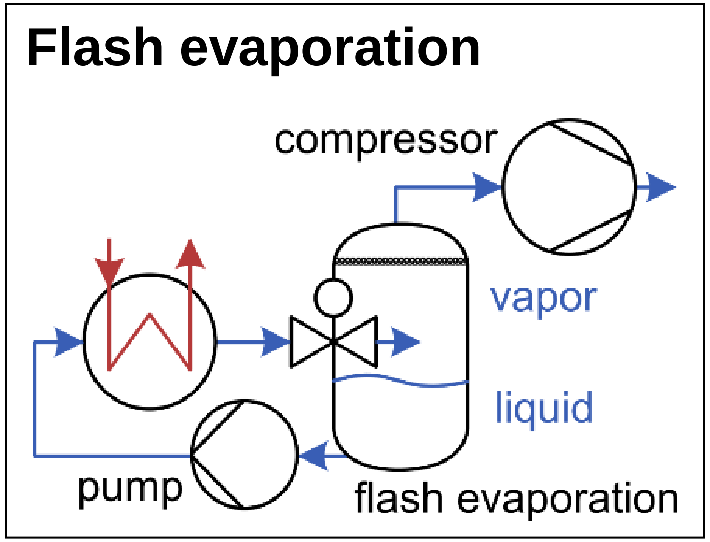

Water Injection
ram air heat exchanger
with injection
water
fan
ram air
water tank


Cooling Tower
cooling tower
fan
hot water
ram air
moist air
pump

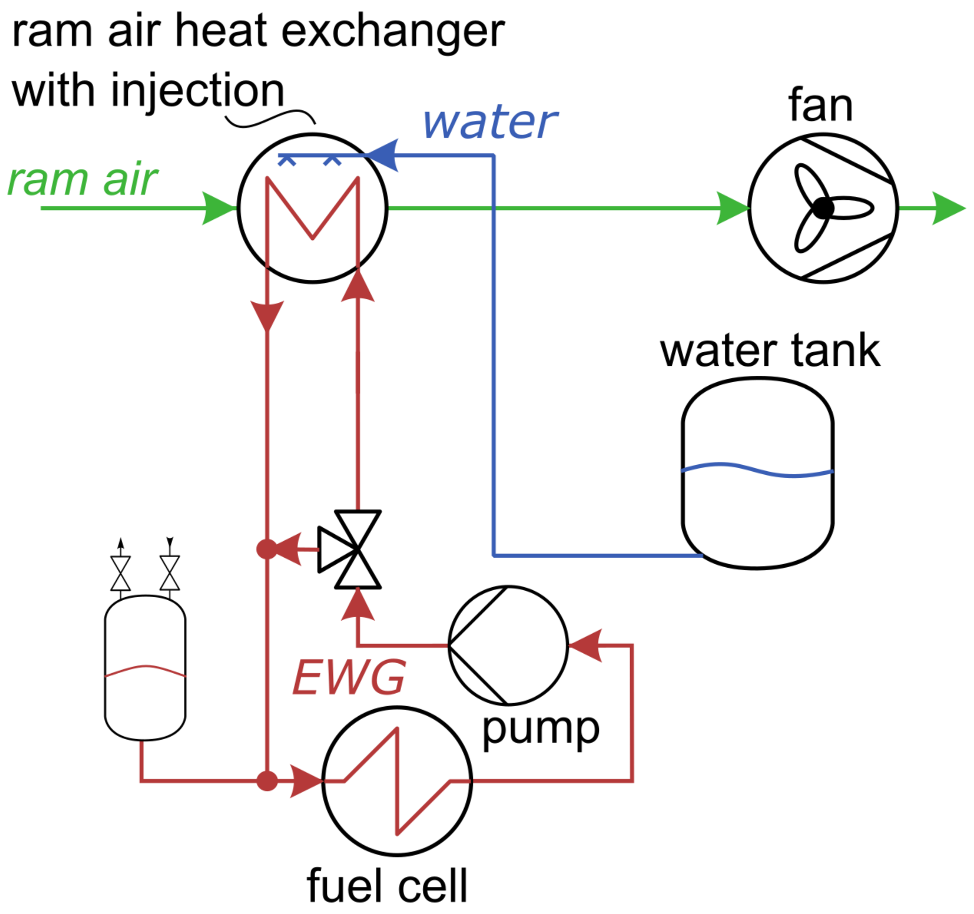

Negative pressure boiling
compressor
boiling
water


ram air
ram air heat exchanger
water evaporation
cooling system
EWG
pump
fuel cell

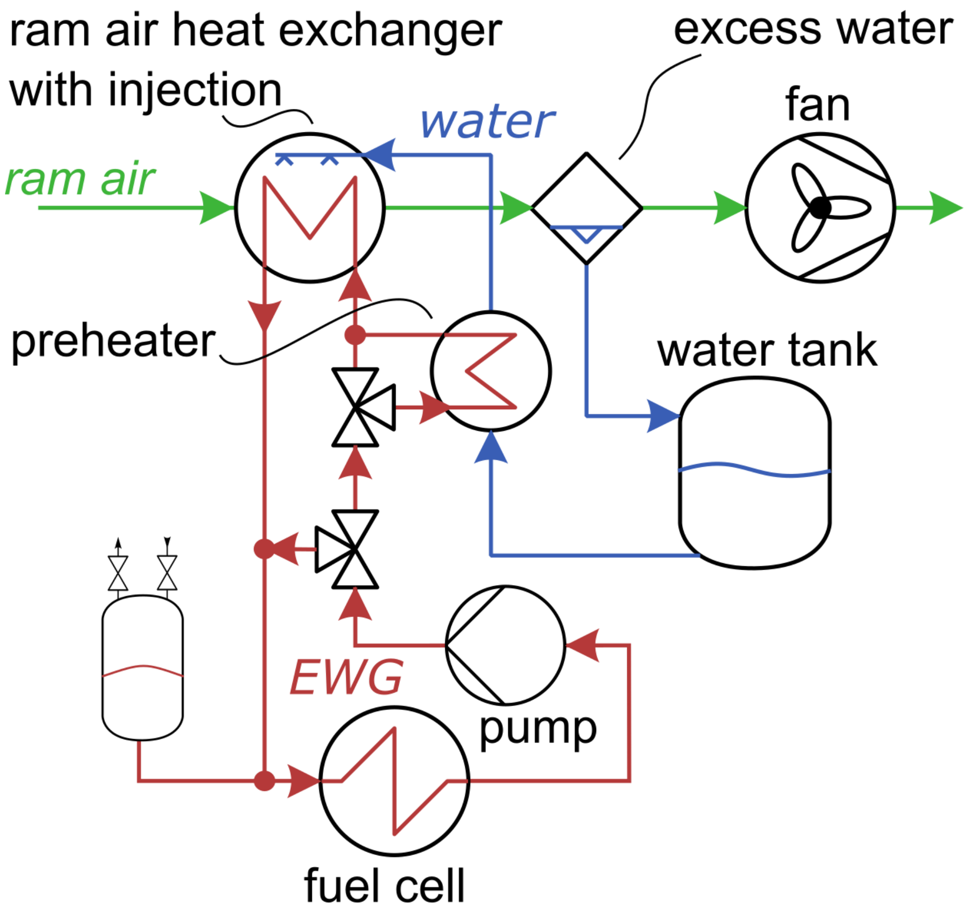

Negative pressure boiling
valve
compressor
boiling


Flash evaporation
compressor
vapor
liquid
pump
flash evaporation

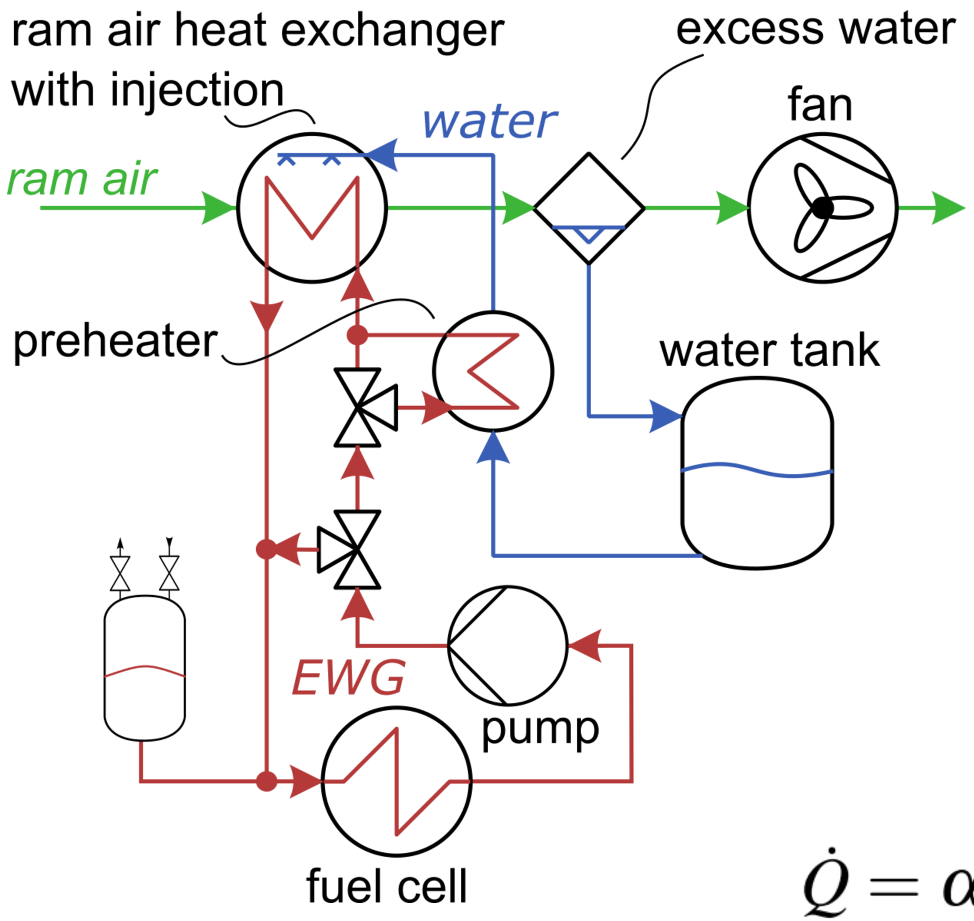
1) Water injection

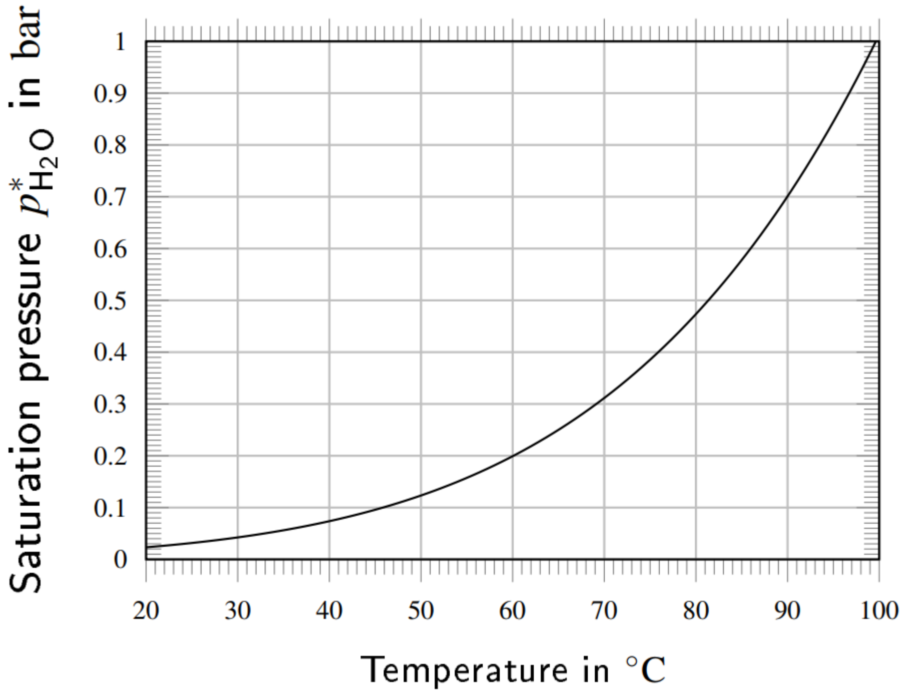


1) Water injection – extension



1) Water injection – temperature influence





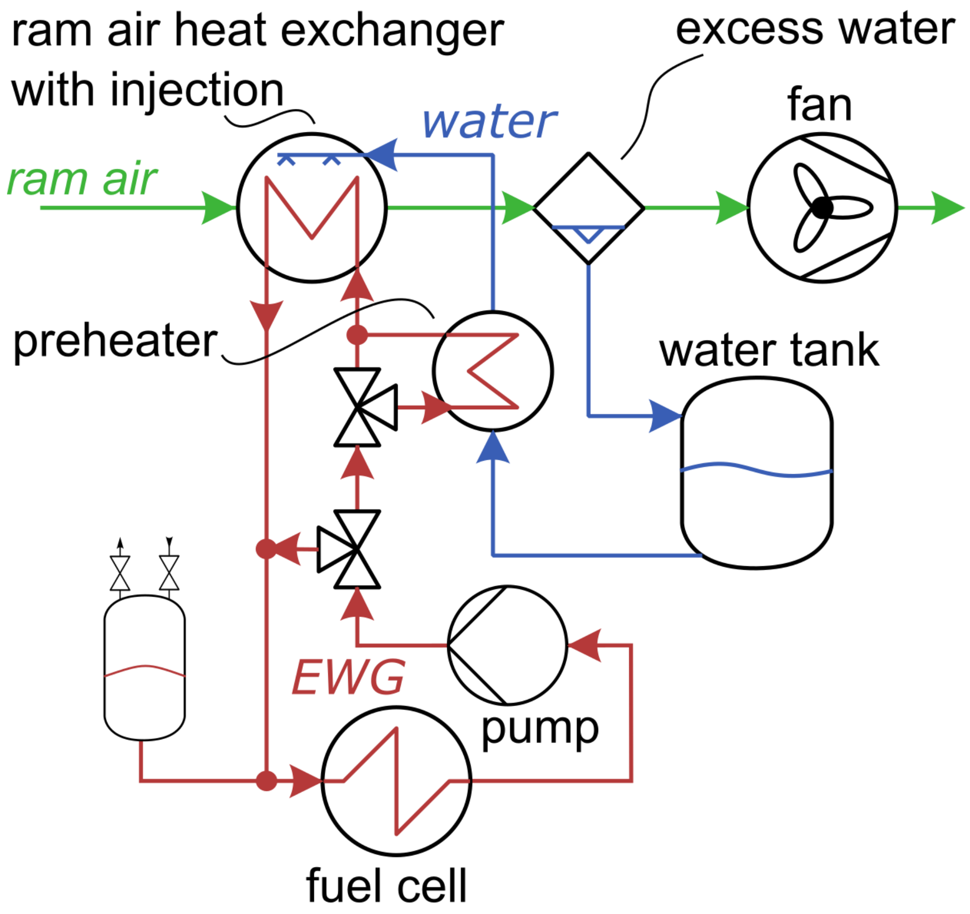
$$\dot{Q} = \alpha A \left(T_{H_2O} - T_{air} \right)$$

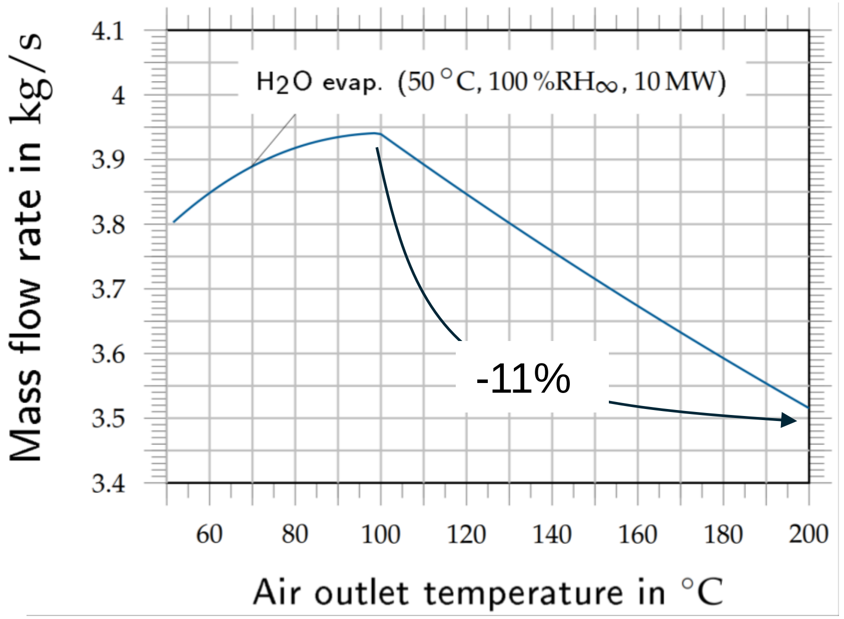
Heat transfer $\propto \Delta T$

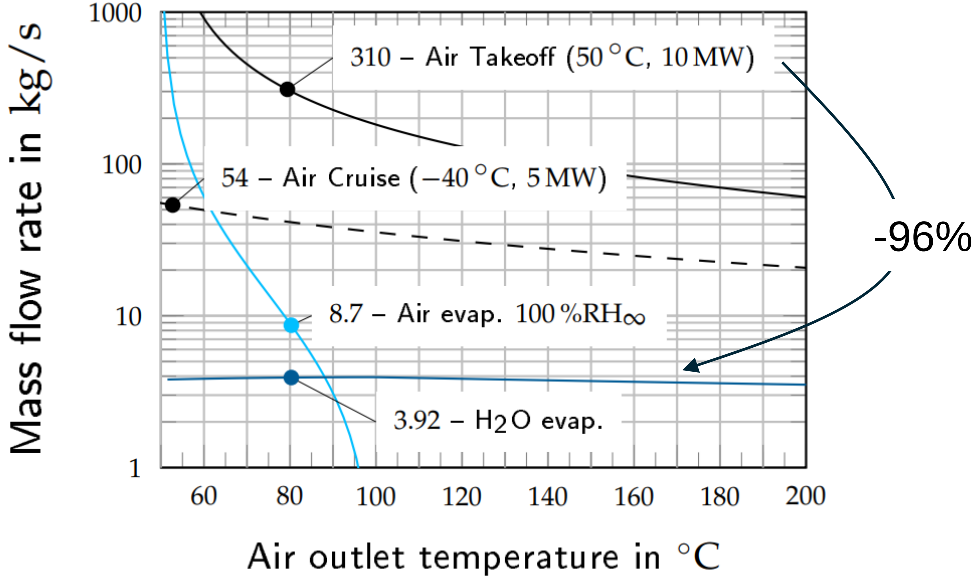
$$\dot{m} = \beta A \left(p^*_{H_2O} - p_{H_2O,air} \right) \frac{\rho}{p}$$

Mass transfer $\propto \exp(T)$

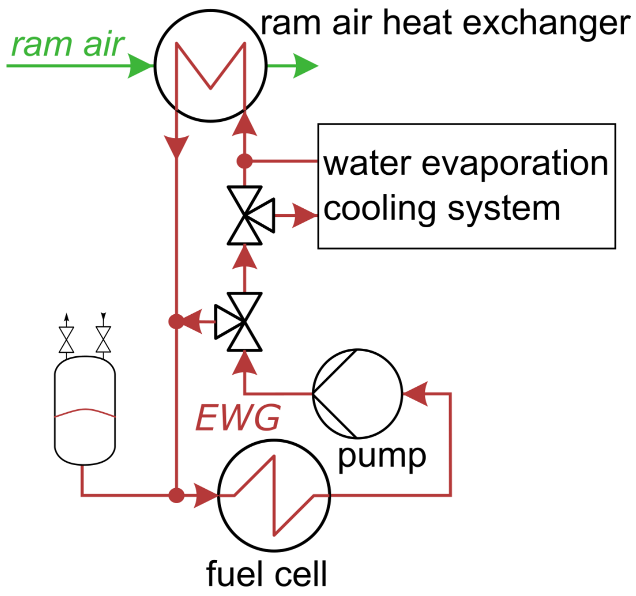
1) Water injection – mass flow rates

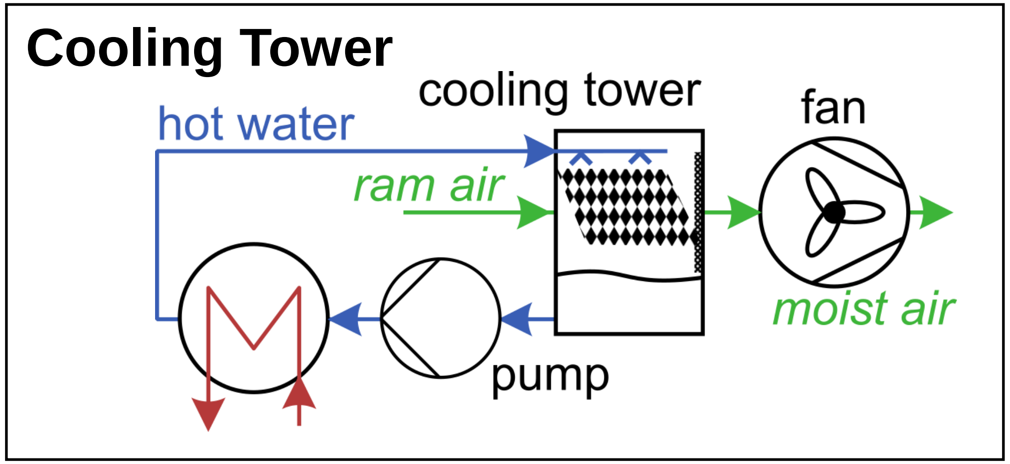






2) Cooling Tower





- Recirculated hot water enters the tower
- Water spreads and wets the fill media → large heat-exchange surface
- Part of the water evaporates into the airflow → remaining water cools
  → Split heat exchange and evaporation (compared to injection into HEX)

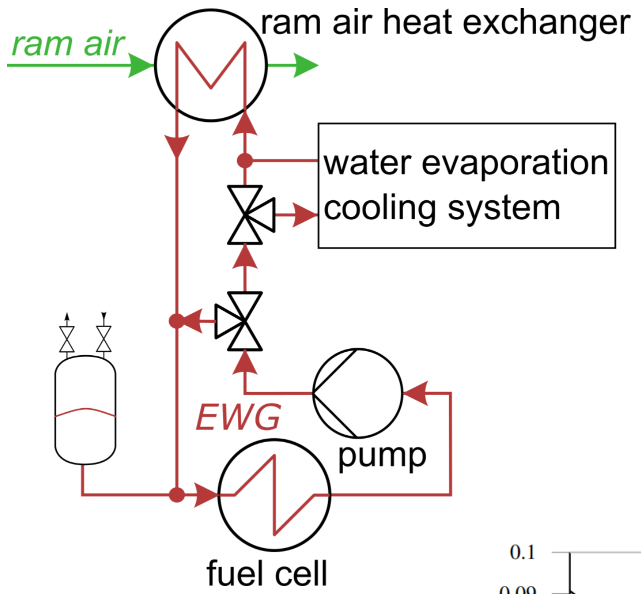
✓ Simplified system interfaces

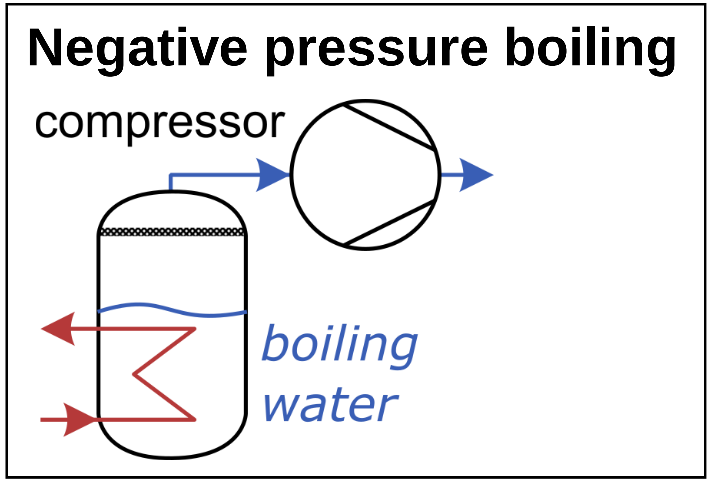
✓ Enhanced optimization opportunities

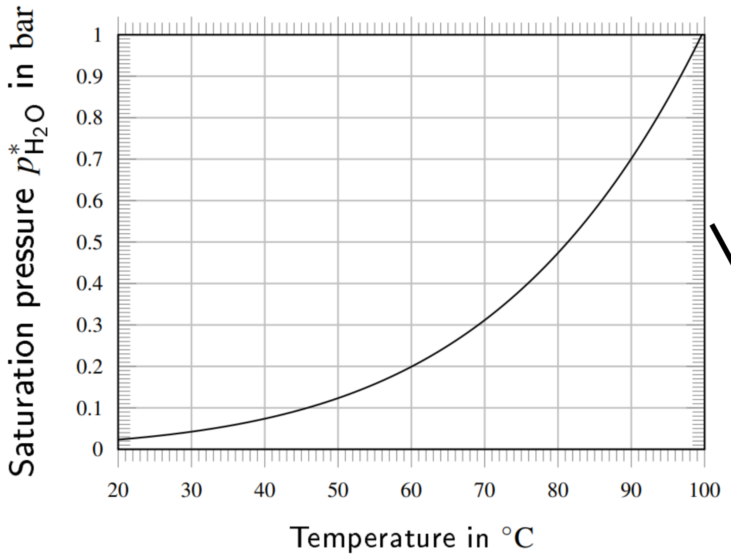
✗ Trade-off: additional system (potential weight)

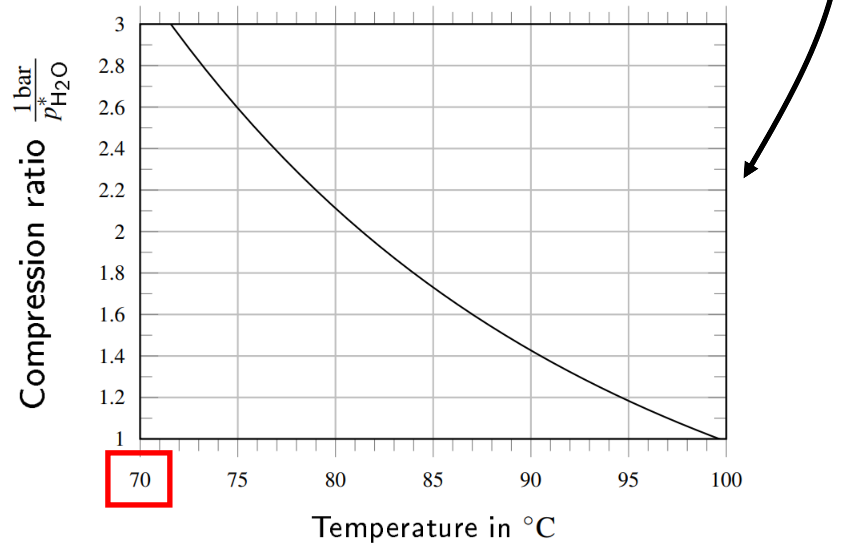
3) Negative Pressure Boiling

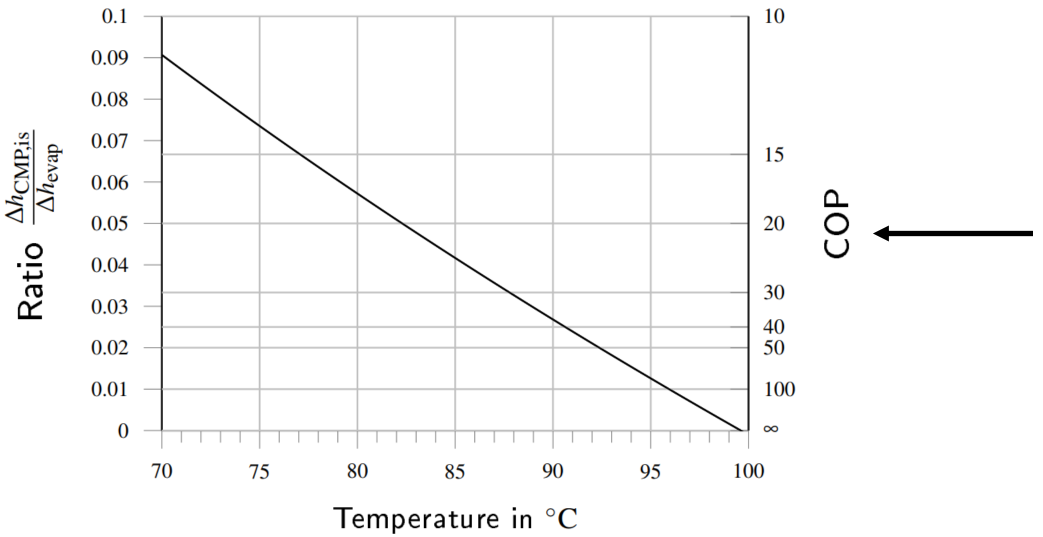
Reduced (negative) pressure → boiling point of water decreases



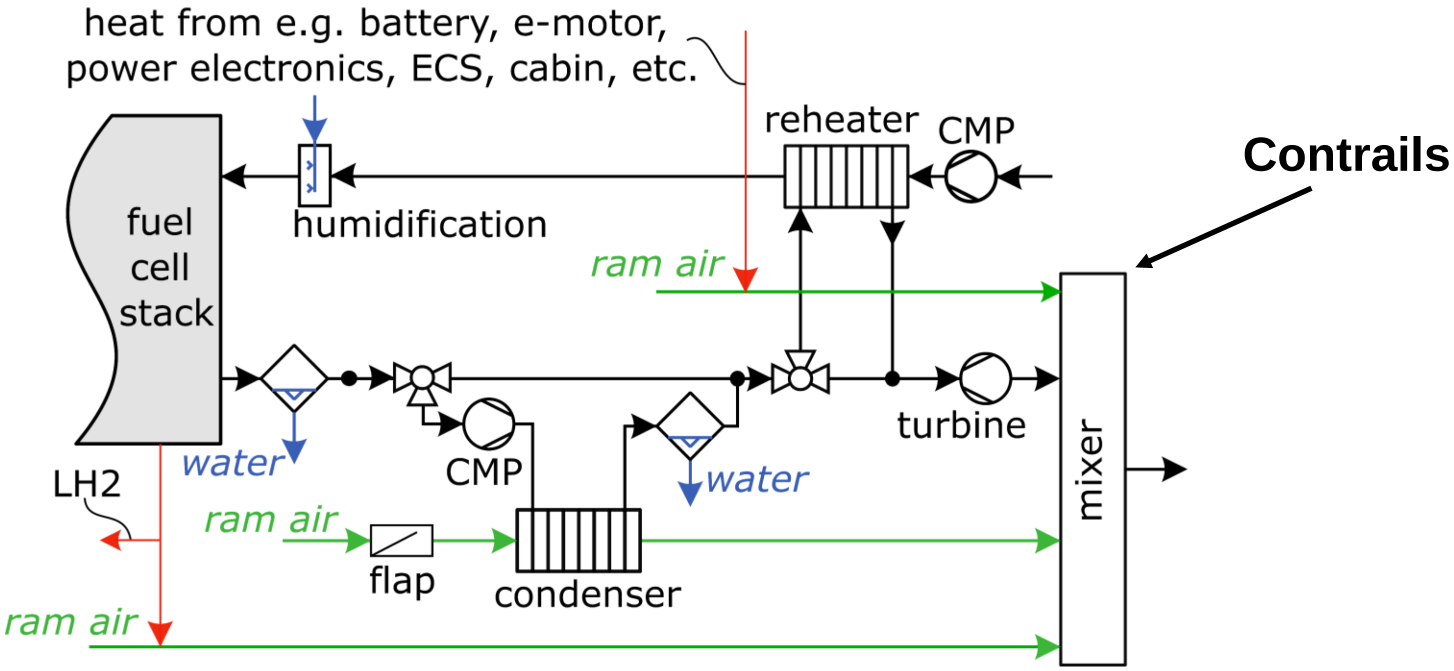








Extraction of water from fuel cell exhaust

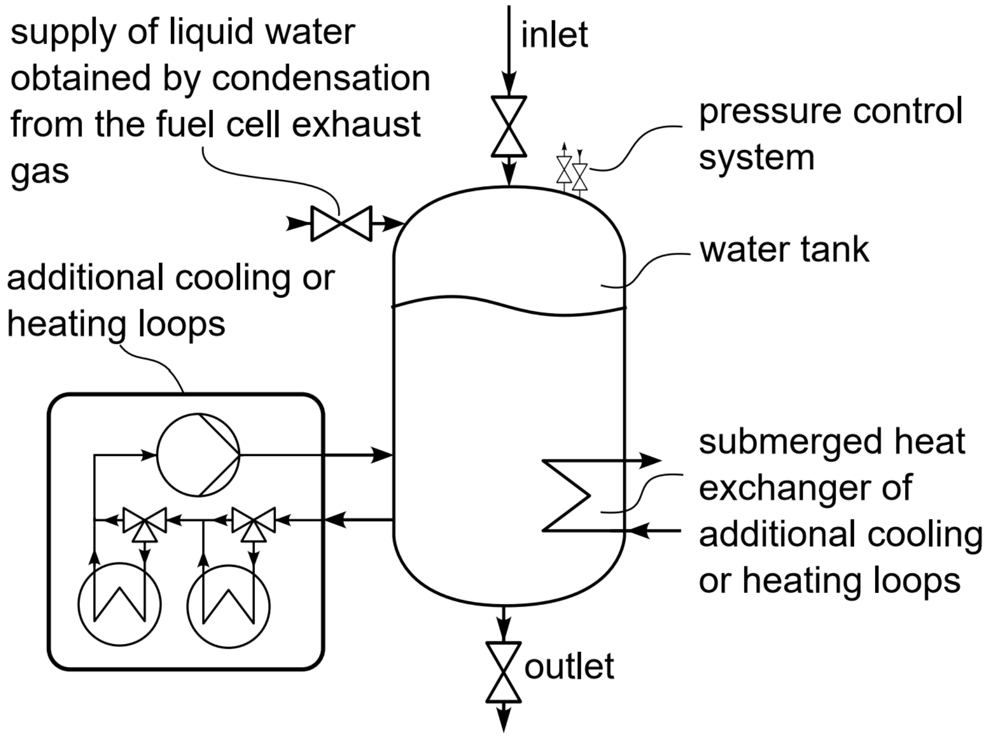


- Additional condenser requires up to $+30\%$ cooling requirement
- Boost system (~5 min at 50 %) recovery in 10 – 20 min possible (relevant for go around)

Water as additional thermal mass (similar to conventional aircraft fuel)

Cooling potential

- 12 – 25 % without evaporation
- 100 % – 200 % with evaporation



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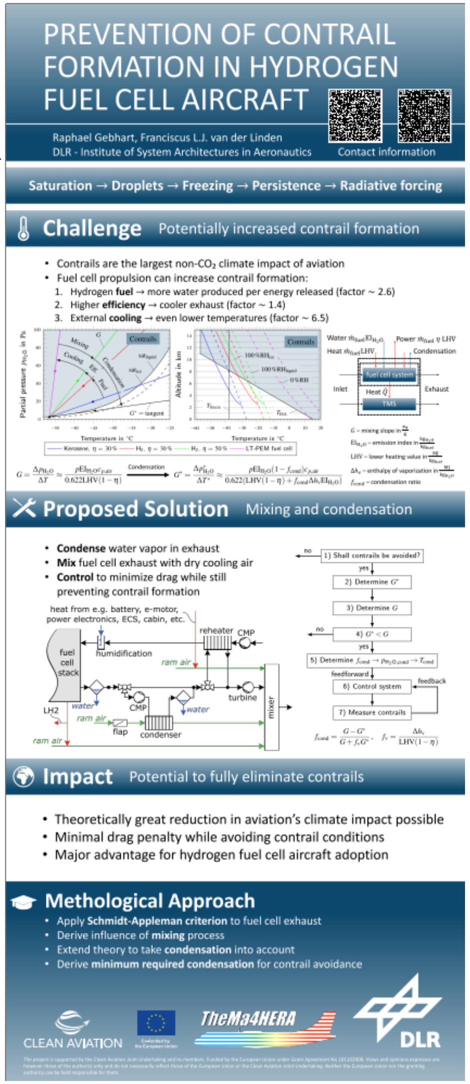
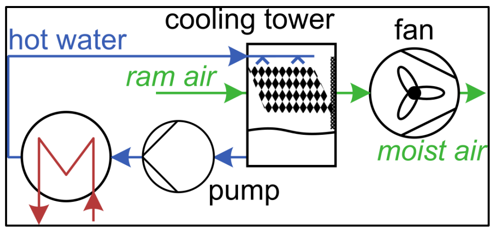
Conclusion

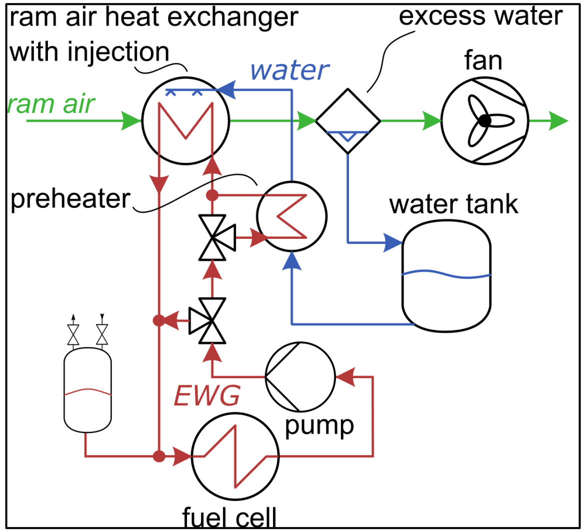
- Significant TMS-induced drag
- Reduction potential using water evaporation fullfilling many requirements
- Hope to inspire further investigations into this approach

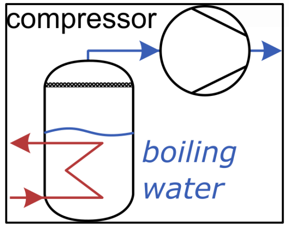
Contrails

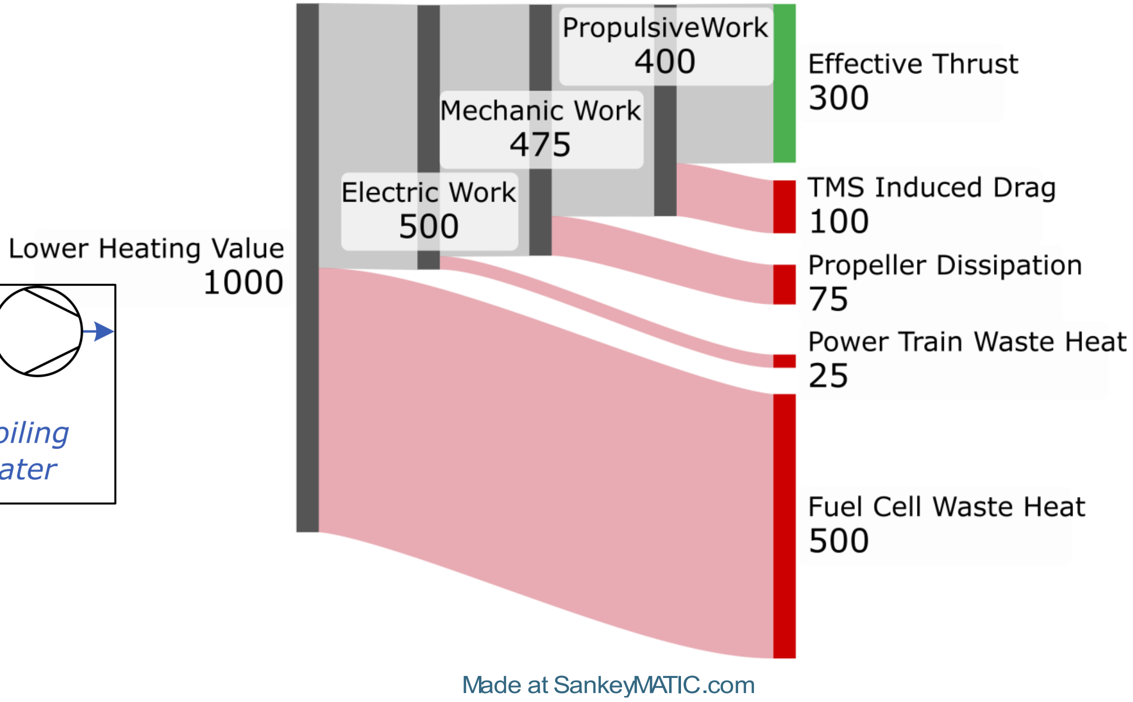


Fuel cell compatible | Reliable | High performance | Low climate impact | Water recovery









Imprint

Topic: Water-Evaporation Supported Fuel Cell Cooling Architectures for Aircraft

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