Appendix M

Time dependent behaviour of pumped two-phase cooling systems
Experiments and Simulations

Henk Jan van Gerner
(NLR, The Netherlands)

Abstract

Two-phase pumped cooling systems (see figure M.1) are applied when it is required to maintain a very stable temperature in a system, for example in the AMS02, which was launched with the space shuttle (in May 2011) and subsequently mounted on the International Space. However, a two-phase pumped cooling system can show complex dynamic behaviour in response to rapid heat load variations. For example, when the heat load is increased, a large volume of vapour is suddenly created, which results in a liquid flow into the accumulator and an increase in the pressure drop. This will result in variations in the pressure and therefore temperature in the system, which are undesired. It is difficult to predict and understand this behaviour without an accurate dynamic model. For this reason, such a model has been developed by NLR. The model numerically solves the one-dimensional time-dependent compressible Navier-Stokes equations, and includes the thermal masses of all the components (see figure M.2 for an example). The model has been used for different projects, and the numerical results show an excellent agreement with experiments. During the presentation, I will discuss different pumped two-phase cooling systems, and a comparison between simulations and experiments.

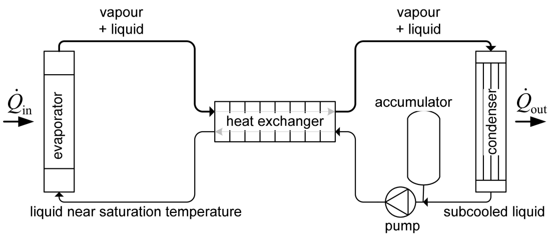


Figure M.1: Schematic drawing of a two-phase pumped cooling system

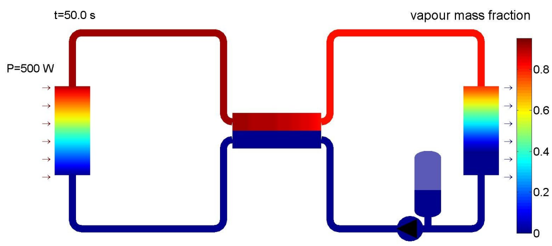
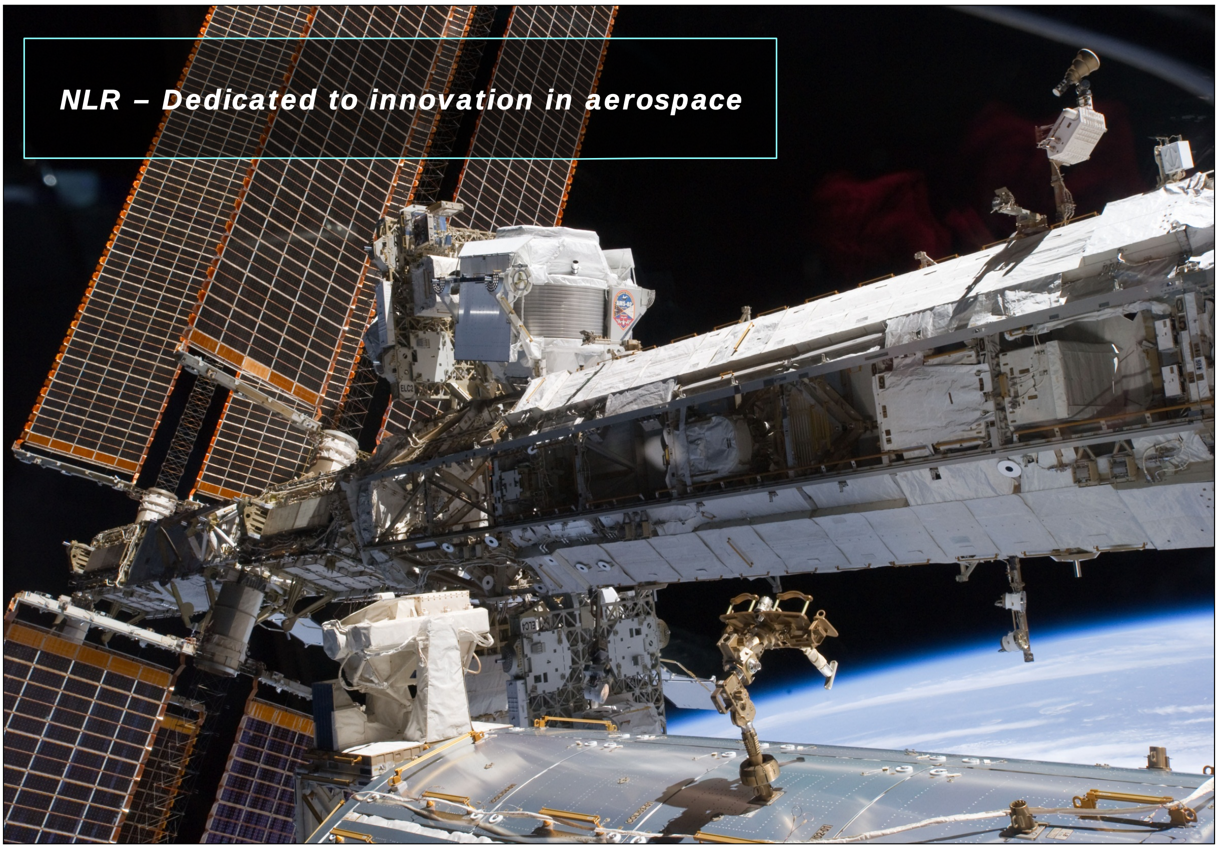


Figure M.2: Calculated vapour mass fraction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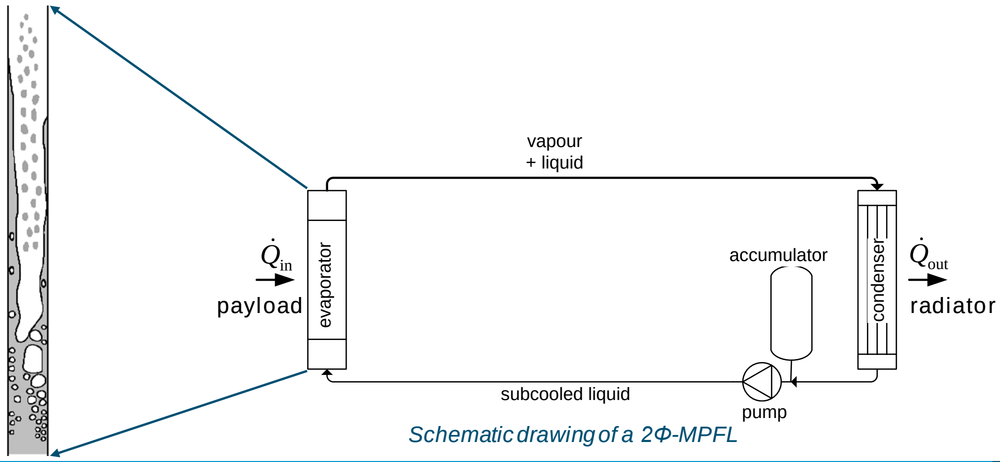
Time-dependent behaviour of pumped two-phase cooling systems: Experiments and Simulations
Henk Jan van Gerner, Niels Braaksma
Nationaal Lucht- en Ruimtevaartlaboratorium – National Aerospace Laboratory NLR

Two-phase Mechanically Pumped Fluid Loop

- In a 2Φ-MPFL, thermal energy is transported by circulating a fluid which evaporates and condenses at almost constant temperature



Schematic drawing of a 2Φ-MPFL

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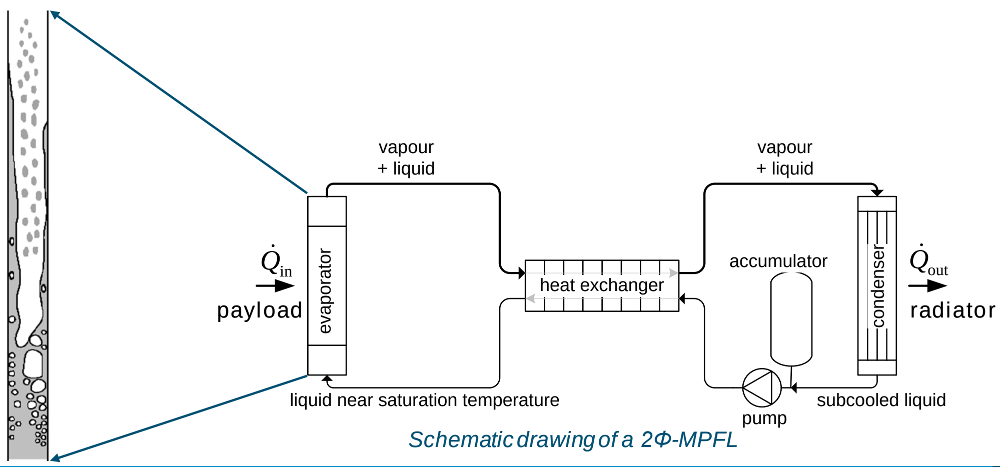

Schematic drawing of a 2Φ-MPFL

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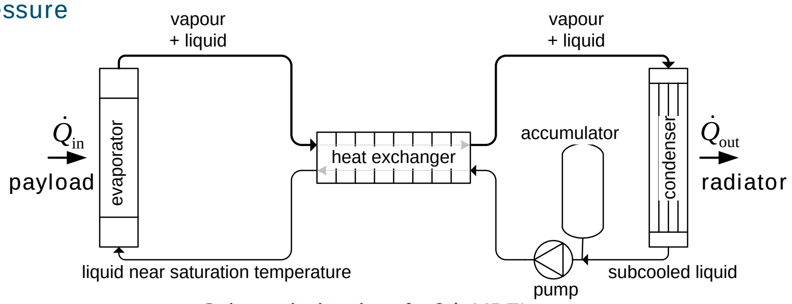
Two-phase Mechanically Pumped Fluid Loop

- In a 2Φ-MPFL, thermal energy is transported by circulating a fluid which evaporates and condenses at almost constant temperature
- Advantages compared to single-phase (e.g. water, glycol) cooling:
  - very uniform temperature
  - low mass flow (typically 10 to 100 times lower)
  - much smaller tubing diameter
  - much higher heat transfer coefficient
- Accumulator controls the saturation temperature/pressure in the loop



Schematic drawing of a 2Φ-MPFL

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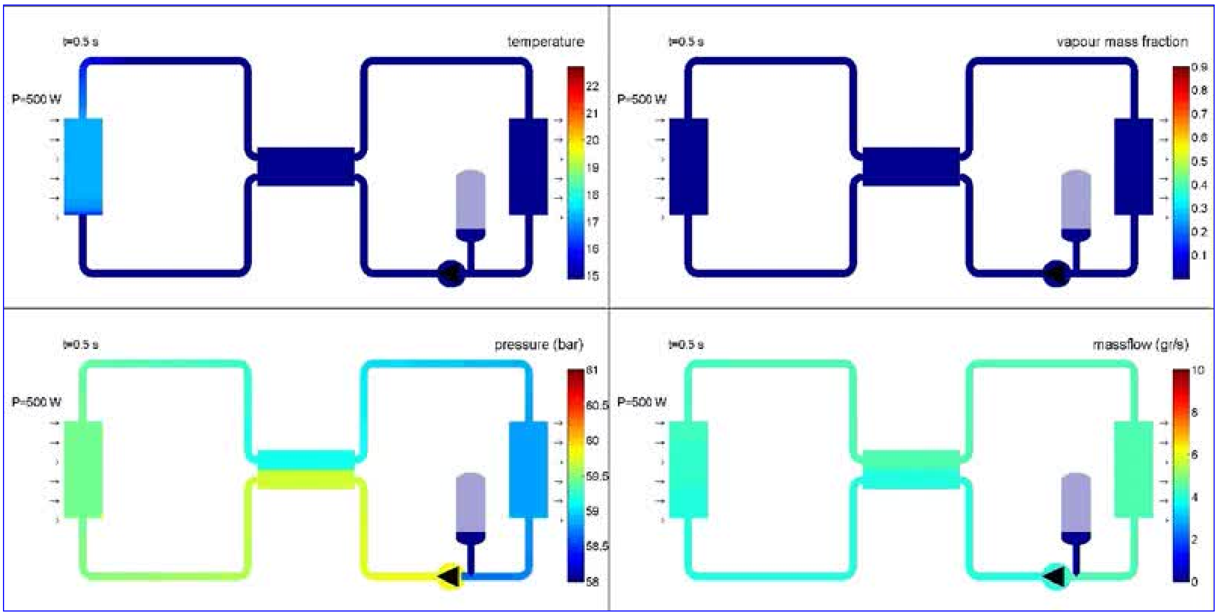

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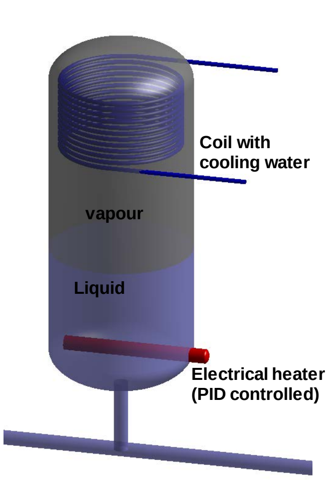
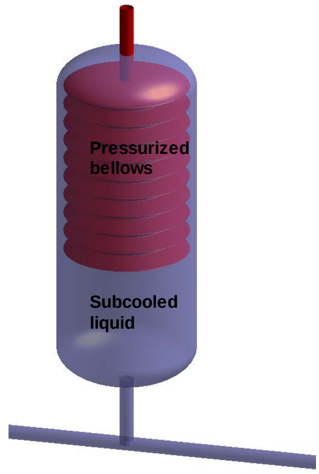
Two basic types of accumulators





Heat Controlled Accumulator (HCA)

- responds slower (depending on cooling capacity)
- simple, low mass, reliable
- Most often used

Pressure Controlled Accumulator (PCA)

- responds very fast
- heavy, complex

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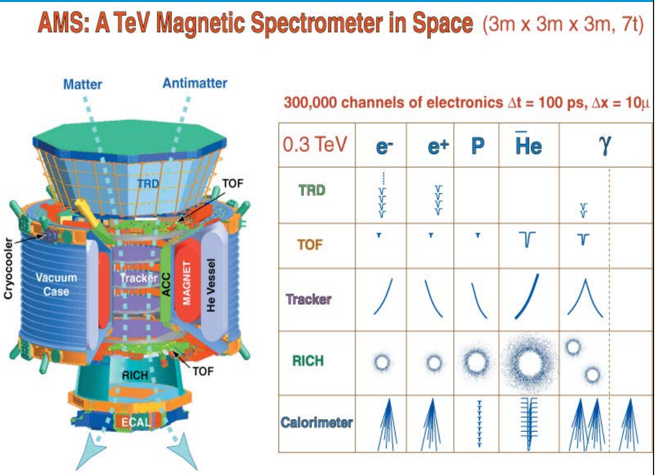
2Φ-MPFL in space

2Φ-MPFL system for AMS02:

- Alpha Magnetic Spectrometer (AMS02) is a large detector (7000kg!) for cosmic particles that was mounted on the International Space Station in May 2011. CO_2 is the thermal control fluid
- NLR is leading the international team for the thermal control system for the AMS02 tracker
- Accumulator is a difficult component in microgravity since the location of liquid and vapour phase is not obvious



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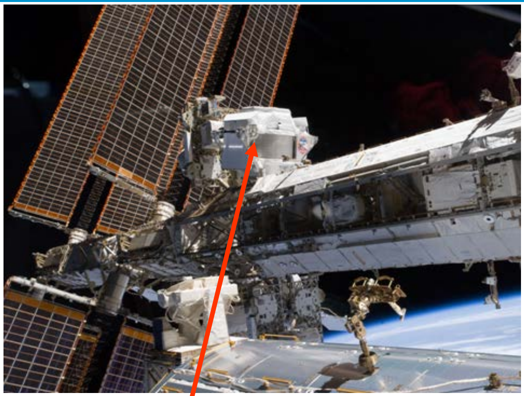

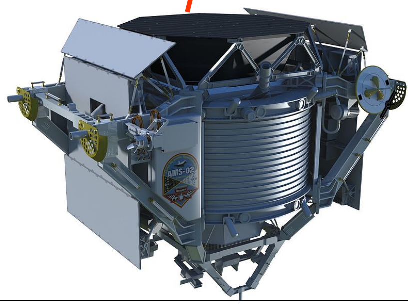

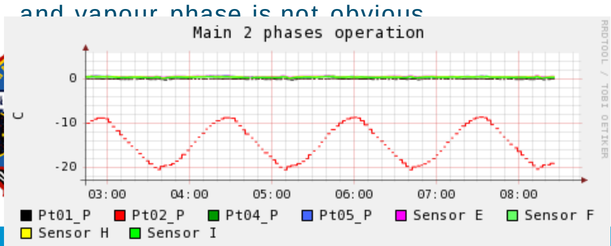

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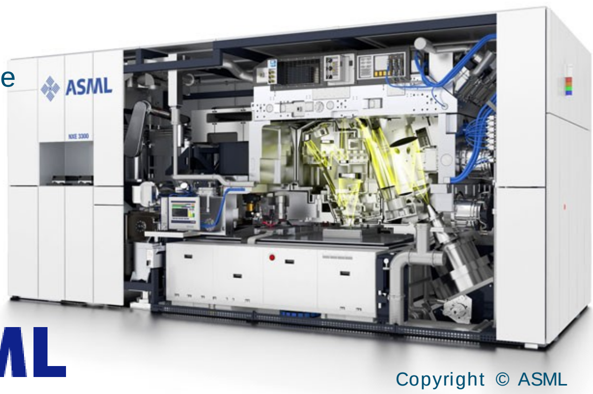
2Φ-MPFL in terrestrial applications

- NLR develops two-phase thermal control systems for ASML and other terrestrial costumers
- In a ASML lithography system, large heat loads have to be removed with very light-weight and small systems
- Furthermore, a very constant temperature has to be maintained
- Simulations has been used to design and built several two-phase thermal control systems for ASML



ASML

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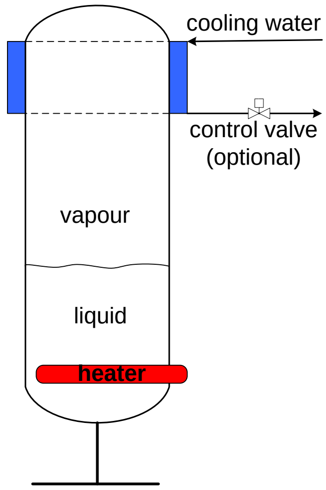
Why do we need a model?

- When the heat load or the heat sink temperature changes (e.g. varying radiator temperature in space application), liquid will flow in/out the accumulator
- As a result, the pressure in the accumulator will change, and therefore the system saturation temperature
- A HCA will respond by heating/cooling inside the accumulator in order to return to the desired pressure/temperature



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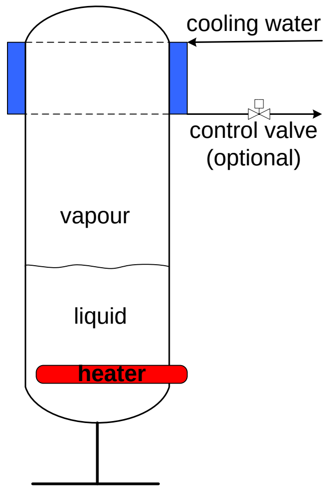
Why do we need a model?

- In principle, the accumulator can keep exactly the desired temperature when the cooling capacity is very large or when the accumulator is very big
- In practice, cooling capacity and accumulator size are limited and the system temperature will vary
- An accurate model of the complete system is required to calculate how much the temperature will vary
- Furthermore, when ‘warm’ liquid flows out of the accumulator, the pump can cavitate. This can also be predicted by the model
- NB: A HCA does not have to be in thermal equilibrium (i.e. the liquid can be cooler than the vapour)



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About the model

- The dynamic model numerically solves (in matlab) the time-dependent 1D Navier-Stokes equations
- The Navier-Stokes equations are slightly modified, such that the maximum timestep is not determined by the sound velocity, but by the fluid velocity. This reduces the calculation time with a factor of ~500 (but soundwaves cannot be modelled)
- The Navier-Stokes equations are discretized using the explicit MacCormack predictor-corrector method
- Thermal masses of the components and tubing are included
- Equations of state (i.e. fluid properties) are obtained from REFPROP
- Heat transfer coefficients for turbulent flow are calculated with empirical relations:
  - Single-phase: Gnielinski
  - Condensation: Updated Shah correlation
  - Evaporation: Kandlikar or Cooper's pool boiling correlation with dryout model
- Frictional pressure drop for turbulent flow is calculated with empirical relations
  - Single-phase: Coolebrook
  - Two-phase: Müller-Steinhagen and Heck, Friedel, or linear relation
- Different types of accumulators are implemented

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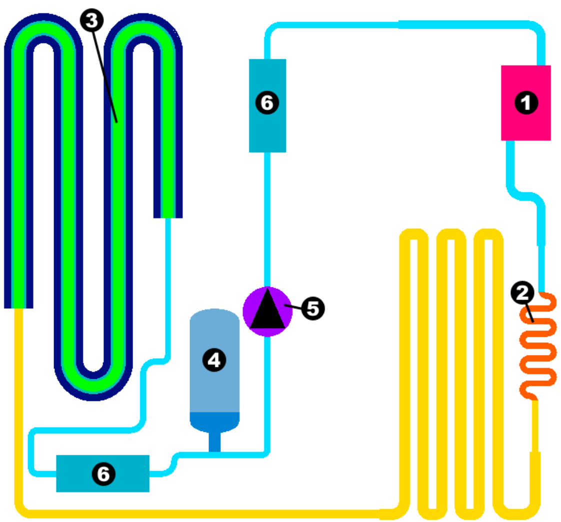
Comparison between the model and experiments

- In order to validate the model, experiments were carried out with a system filled with CO_2



1. Preheater
2. Evaporator
3. Condenser
4. Accumulator
5. Pump
6. Mass flow meters

Schematic drawing of the test setup

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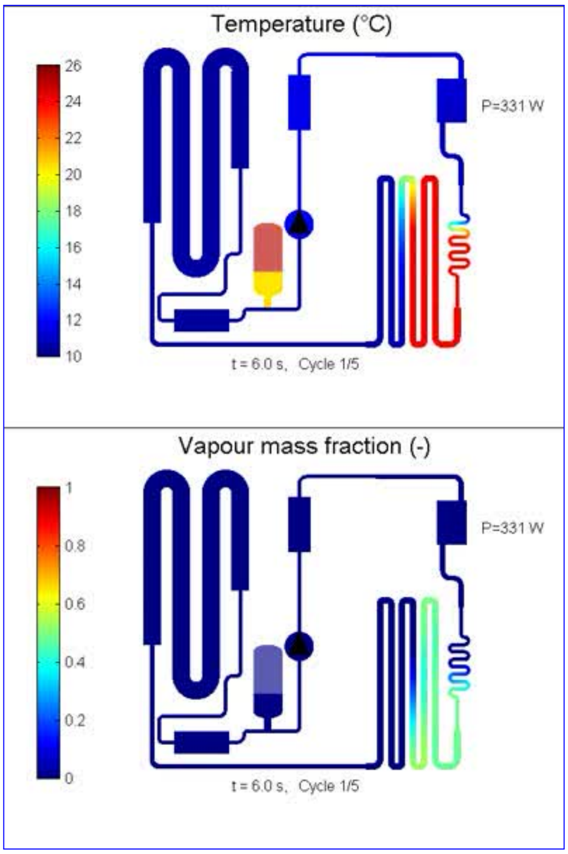

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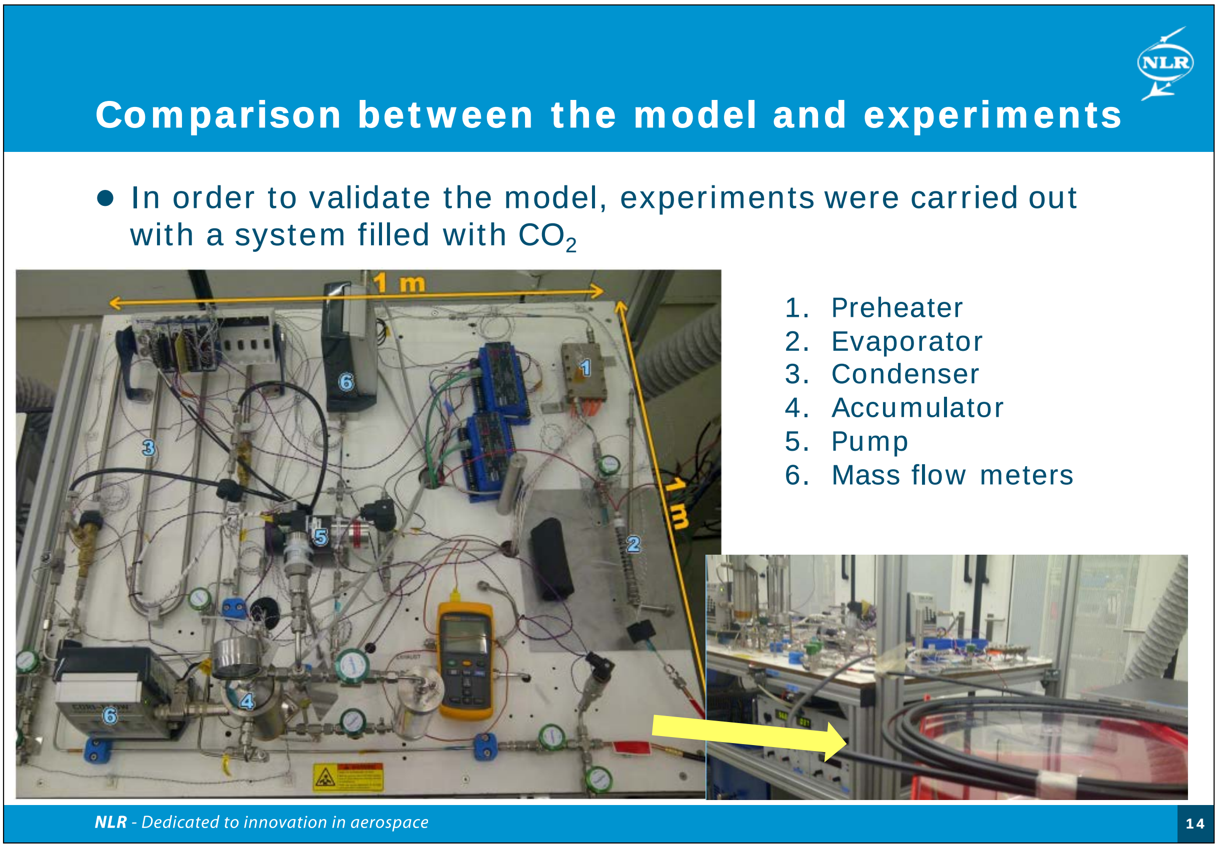

Comparison between the model and experiments

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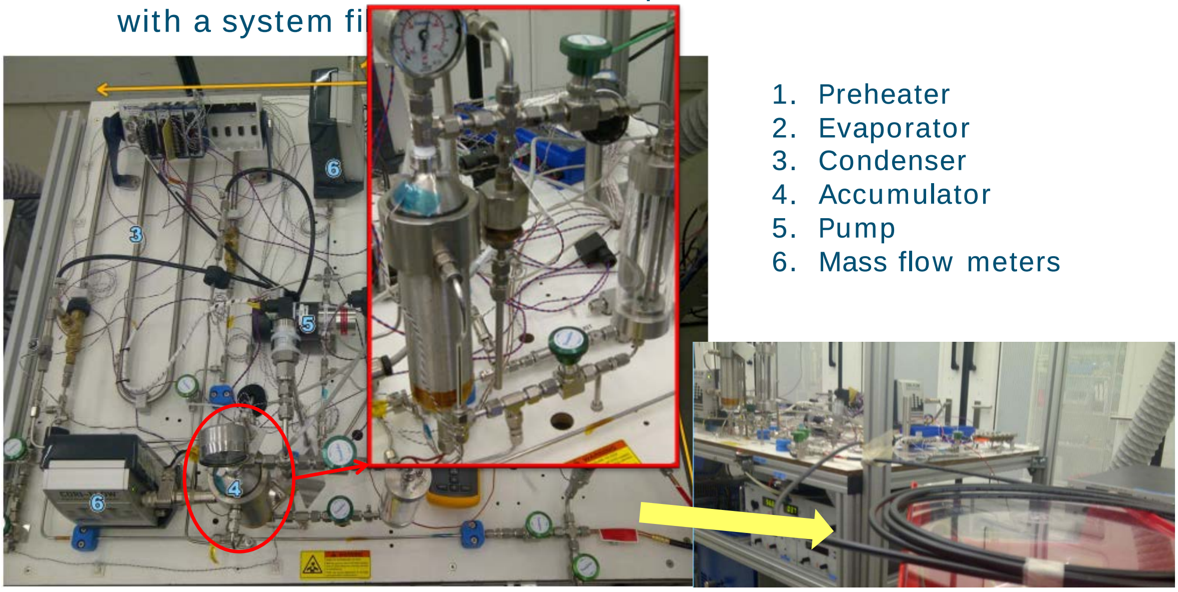

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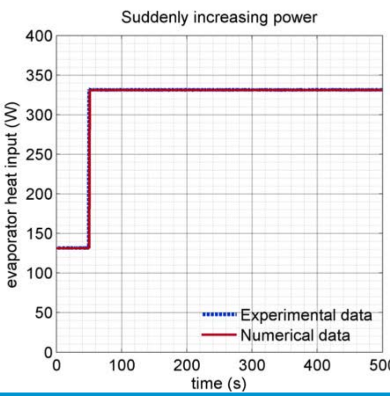
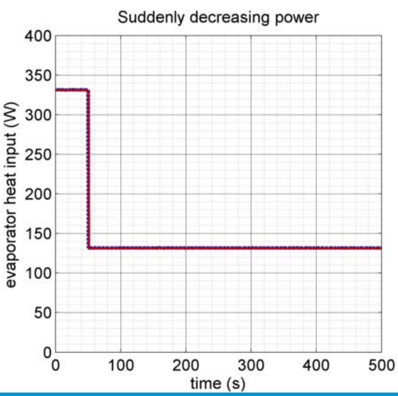
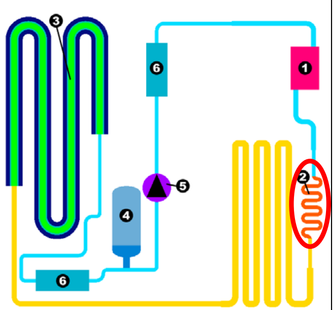
Comparison between the model and experiments

Power:

- The heat input in the evaporator is changed from 131W to 331W
- The preheater is not used → it is just a thermal mass







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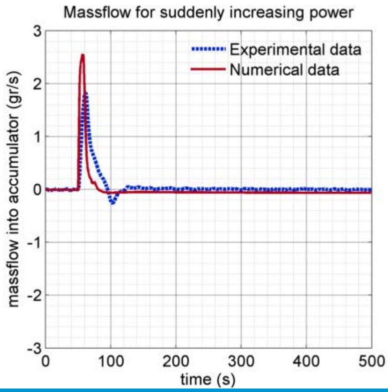
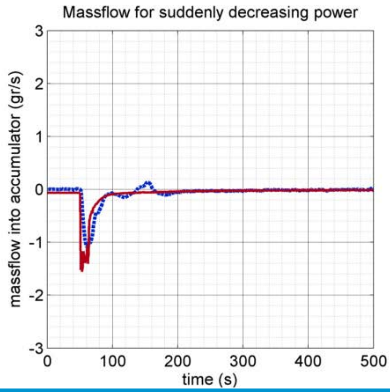
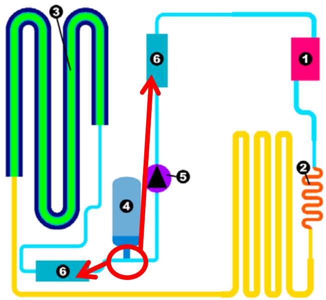
Comparison between the model and experiments

Massflow:

- Massflow into the accu is the difference between the two massflow meters
- As a result of an increase in evaporator power, liquid will flow into the accumulator
- A decrease in evaporator power result in liquid flowing out of the evaporator







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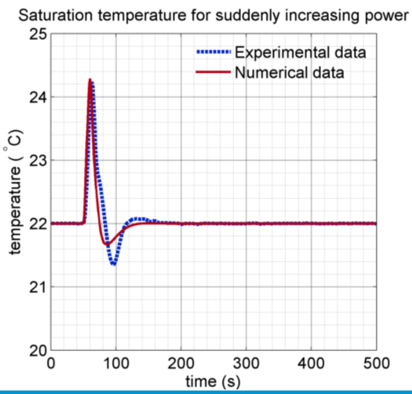
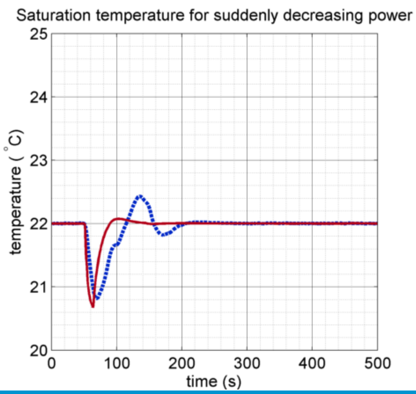
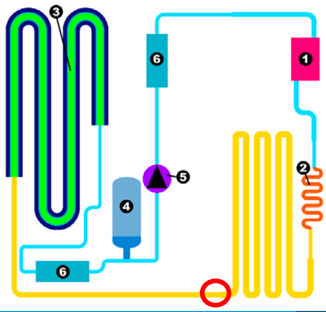
Comparison between the model and experiments

System saturation temperature:

- Due to liquid inflow in the accu (after evaporator power increase), the system pressure and thus temperature will rise
- The accumulator will react and return the temperature to the desired value
- There is an excellent agreement between experiment and simulation







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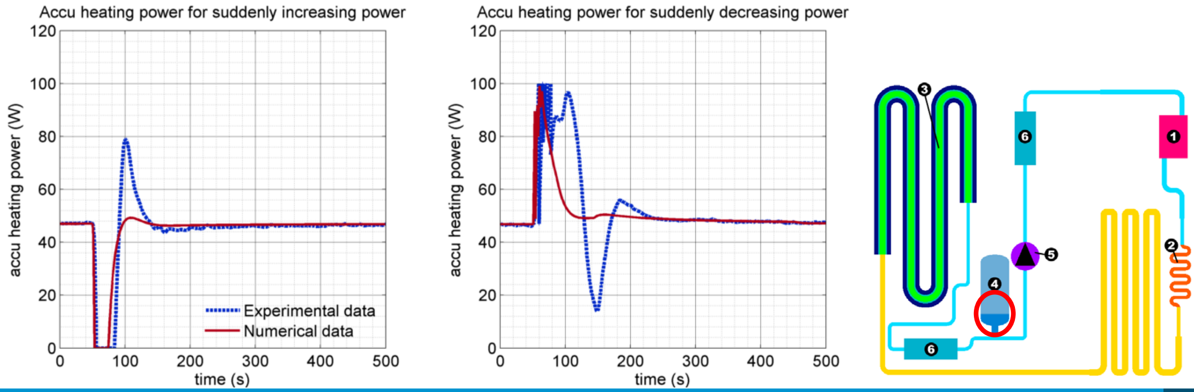
Comparison between the model and experiments

Accu heat/cooling power:

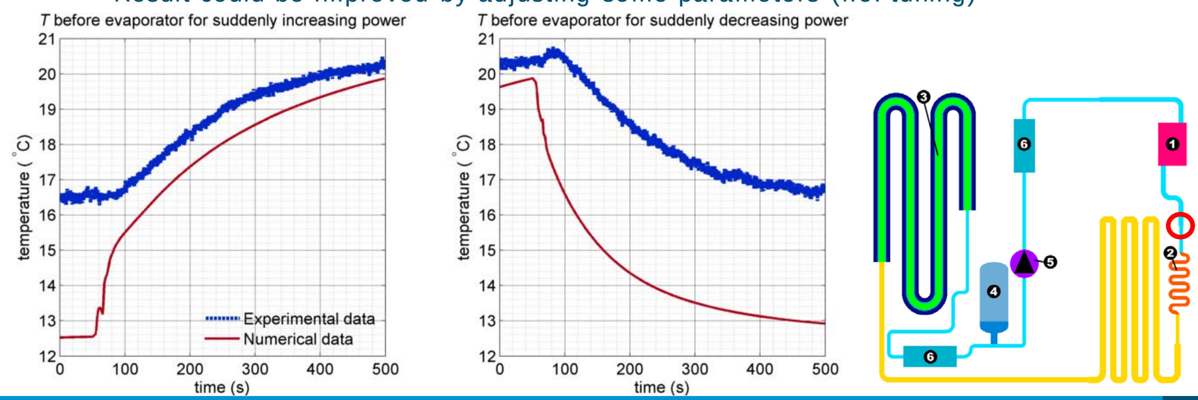
- The accu cooling capacity is 43W. This was known from previous experiments, but this can also be calculated directly. The steady-state heating power compensates for the cooling power
- The accu heating power is PID controlled. The PID parameters in the model and experiment are the same
- More accu cooling power results in better temperature stability



Comparison between the model and experiments

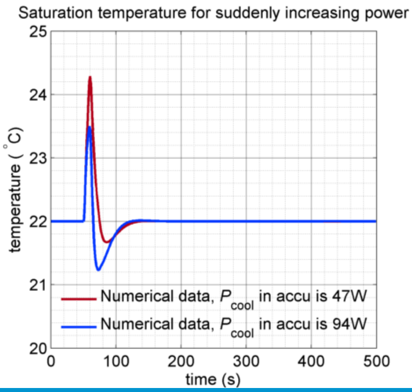
Evaporator inlet temperature:

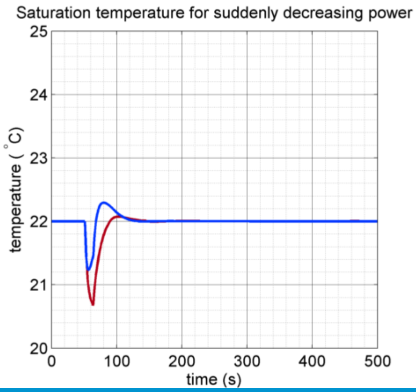
- There is a large difference between the simulated and experimental inlet temperature
- This is caused by a difference in pump efficiency and inaccuracy in HTC:
  - Simulation: Efficiency assumed to be constant at 15%
  - Experiment: Gear pump with variable efficiency, cooling water massflow not known
- However, the difference does not influence the system behavior → $\Delta x = \frac{C_p \Delta T}{H_{lv}} \approx 0.1$
- Result could be improved by adjusting some parameters (i.e. tuning)

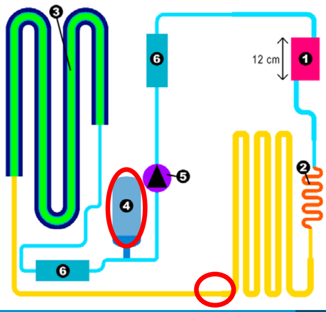


Effect of accumulator cooling power

- Increasing the accu cooling power, results in smaller variations in the system temperature
- However, this is often difficult to achieve in practice, and it results in an increase in steady-state heating power
- When a low energy consumption is important, Peltier elements are used to provide both heating and cooling in the accu (as in AMS02)







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Conclusions and further developments

Conclusions

- The saturation temperature in a system will vary as a result of heat load variations
- The model is able to predict the saturation temperature variations accurately

Further developments

- Simulations have been carried out with different fluids (CO_2, R134a, R152a, R245fa). However, tests have only been carried out with CO_2
  → Validate model with other fluids
- Use the model for Heat Pump applications (i.e. refrigerator loops)
- Implement accumulator with Peltier heating/cooling instead of water cooling

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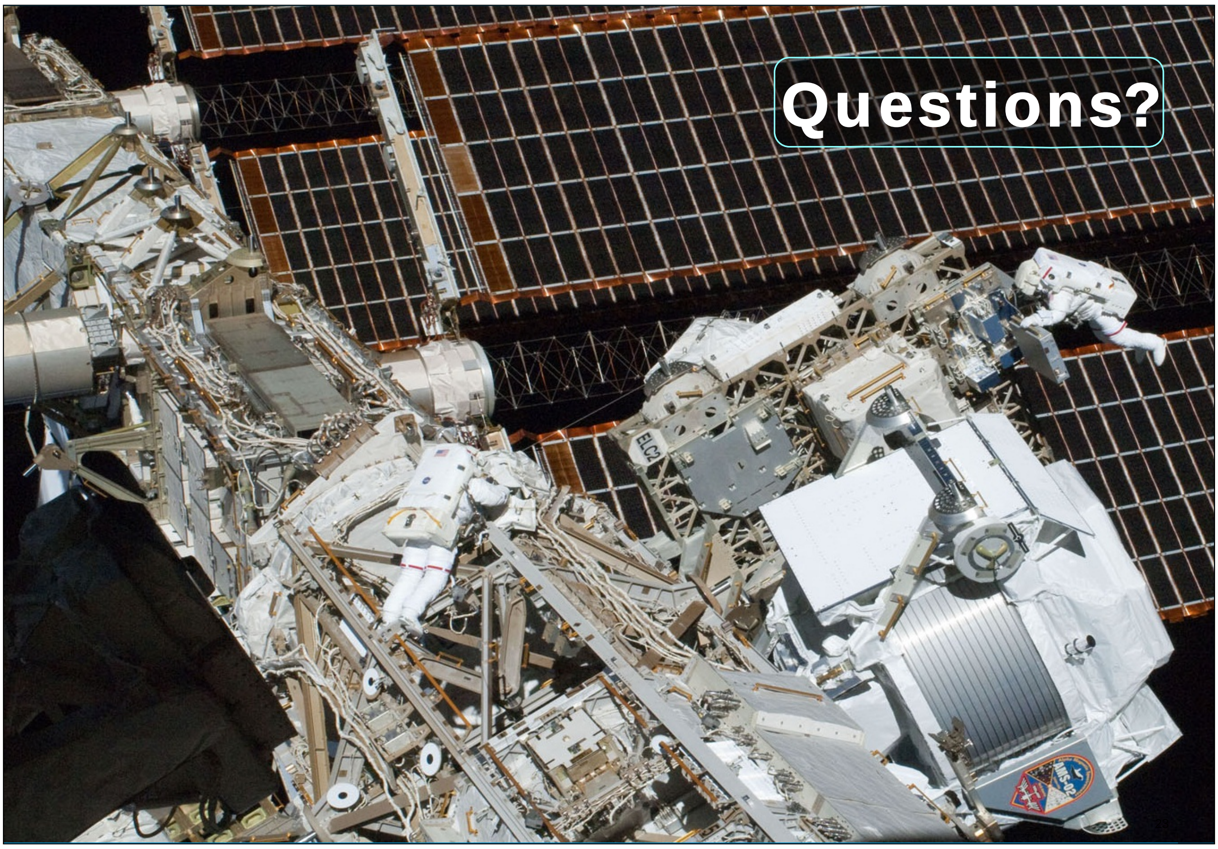
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