Appendix D

Fluid-selection tool

Henk Jan van Gerner
(NLR, The Netherlands)

Abstract

Fluid selection is one of the first and most important steps for the design of a thermal control system. The usual approach to fluid selection is to manually evaluate many different fluids. However, this is a very time-consuming process, since the number of fluids to choose from is very large, and the best fluid strongly depends on the application and temperature range. Furthermore, a potentially suitable fluid can be overlooked when fluids are manually selected. For these reasons, NLR developed a systematic, automated, fluid-selection tool. This fluid selection tool is implemented in Matlab, and it uses a figure of Merit to select the most suitable fluids from the REFPROP database. In this presentation, the use of the fluid selection tool is demonstrated for 4 different applications: Heat Pipe, Loop Heat Pipe, Two-phase mechanically pumped loop, and a heat pump. For example, it is explained why CO_2 is used in the thermal control system of AMS02 (which was launched with the space shuttle in May 2011 and subsequently mounted on the International Space Station) and why isopentane is selected for an ESA Heat Pump application.

With the fluid selection tool, fluids can be selected which would have been overlooked without the use of the figure of Merit. Furthermore, the tool offers a large saving in ccosts and time since the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button.

NLR Dedicated to innovation in aerospace

Fluid selection tool

Johannes van Es (presenter), Henk Jan van Gerner

28th European Space Thermal Analysis Workshop, 14-15 October 2014, ESTEC

Nationaal Lucht- en Ruimtevaartlaboratorium – National Aerospace Laboratory NLR

Introduction

- Fluid selection is one of the first and most important steps for the design of a thermal control system
- The number of fluids to choose from is very large, and the best fluid strongly depends on application and temperature range
- Usually, the approach to fluid selection is to manually evaluate many different fluids

***NLR** - Dedicated to innovation in aerospace* 3

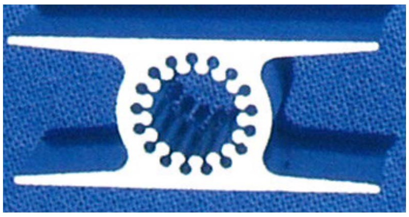
Introduction

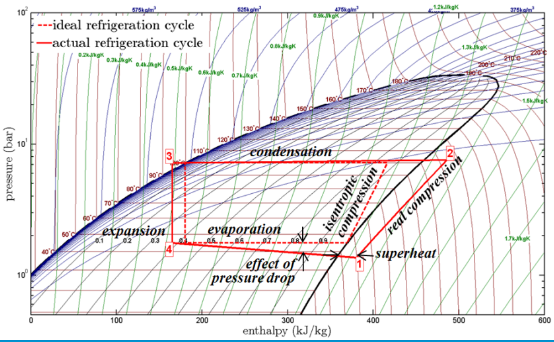
- This is a very time-consuming process
- Furthermore, very often the wrong fluids are analyzed and 'good' fluids are missed:
  - Standard fluids often have a poor performance in space applications, because the temperature range is usually very different than for terrestrial applications
  - Fluid flammability and/or toxicity are less an issue for space applications than for terrestrial applications
- Because of these reasons, NLR developed a systematic, automated, fluid-selection tool

***NLR** - Dedicated to innovation in aerospace* 4

Introduction

- The fluid selection uses the 'figure of Merit'
- In this presentation, the use of the figure of Merit is demonstrated for 4 different applications
  - Heat pipe
  - Loop Heat Pipe/Capillary Pumped Loop
  - Two-phase mechanically pumped loop
  - Heat pump

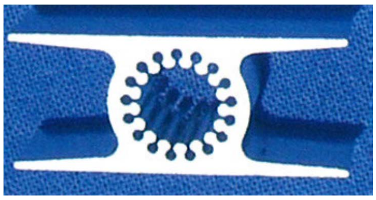


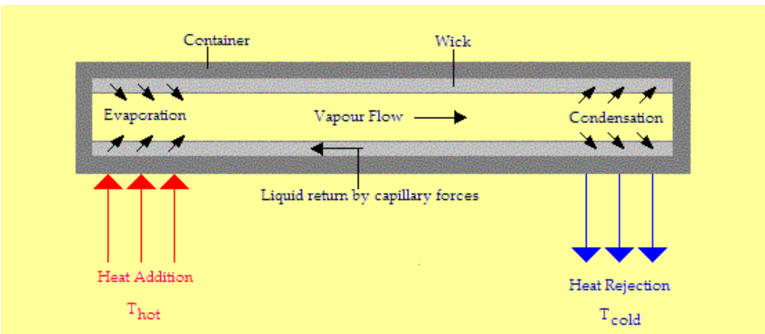


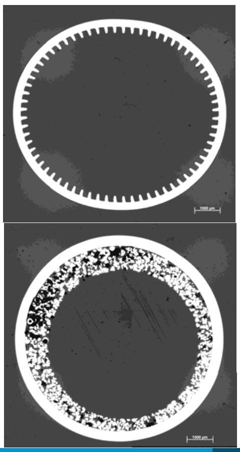
NLR - Dedicated to innovation in aerospace 5

Heat Pipes

- Heat Pipes are capillary driven two-phase heat transfer devices
- Can transport large amounts of thermal energy with only a small ΔT (~10000 better than copper)
- Usually water or ammonia as working fluid







NLR - Dedicated to innovation in aerospace 6

Heat pipes

- There are several limits to the heat transport capacity of a heat pipe (capillary limit, entrainment limit, sonic limit etc.)
- The capillary limit is usually the most restrictive: $\Delta p_{\text{cap, max}} > \Delta p_{\text{friction}}$
- From this capillary limit, the maximum heat transport capacity P is derived:

$$P \propto \overbrace{\frac{d^3 N}{L}}^{\text{geometry dependent}} \overbrace{\boxed{\frac{\rho_l h_{lv} \sigma}{\mu_l}}}^{\text{fluid dependent}}$$

figure of Merit for heat pipes (well known from literature)

- The fluid selection tool plots the figure of Merit for all the fluids in the REFPROP fluid database

NLR - Dedicated to innovation in aerospace 7

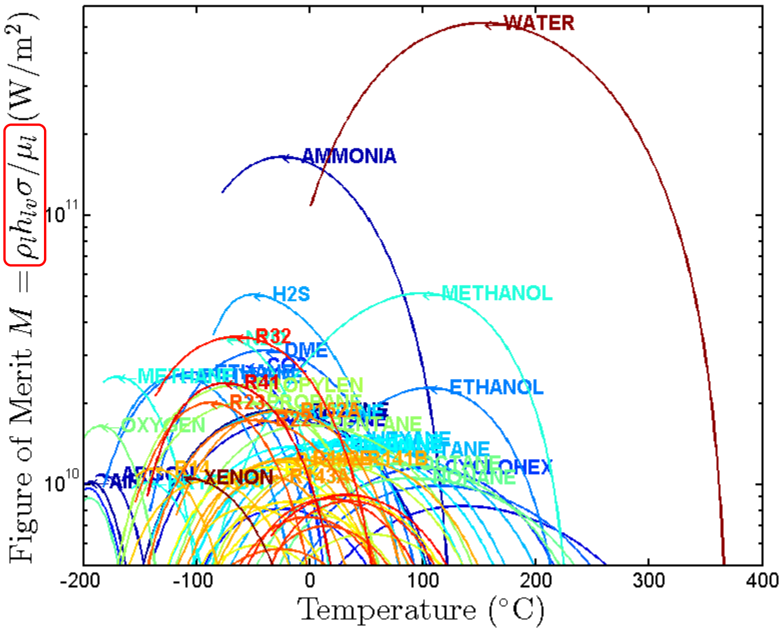
Heat pipes

- There are several lin
(capillary limit, entra
- The capillary limit is
- From this capillary li

geometry dependent fluid c

$$P \propto \frac{d^3 N}{L} \boxed{\frac{\rho_l h_{lv} \sigma}{\mu_l}}$$

- The fluid selection to
REFPROP fluid datab



NLR - Dedicated to innovation in aerospace 8

Loop Heat Pipe

- For a Loop Heat Pipe, the figure of Merit is similar to that of a Heat Pipe
- The major difference with a Heat Pipe is that the vapour pressure drop is usually dominant over the liquid pressure drop
- The flow in the vapour line is generally turbulent
- The figure of Merit for LHP then becomes:

$$M = \frac{\rho_v {h_{lv}}^{7/4} \sigma}{{\mu_v}^{1/4}}$$

figure of Merit for Loop Heat Pipes [1]

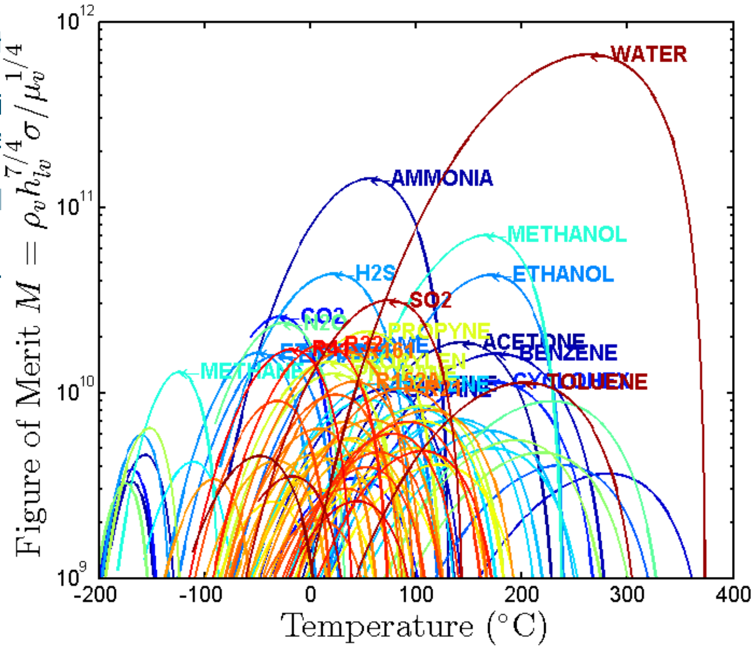
[1] N. Dunbar, P. Cadell, *Working fluids and Figures of Merit for CPL/LHP applications*, CPL-98 Workshop (1998)

***NLR** - Dedicated to innovation in aerospace* 9

Loop Heat Pipe

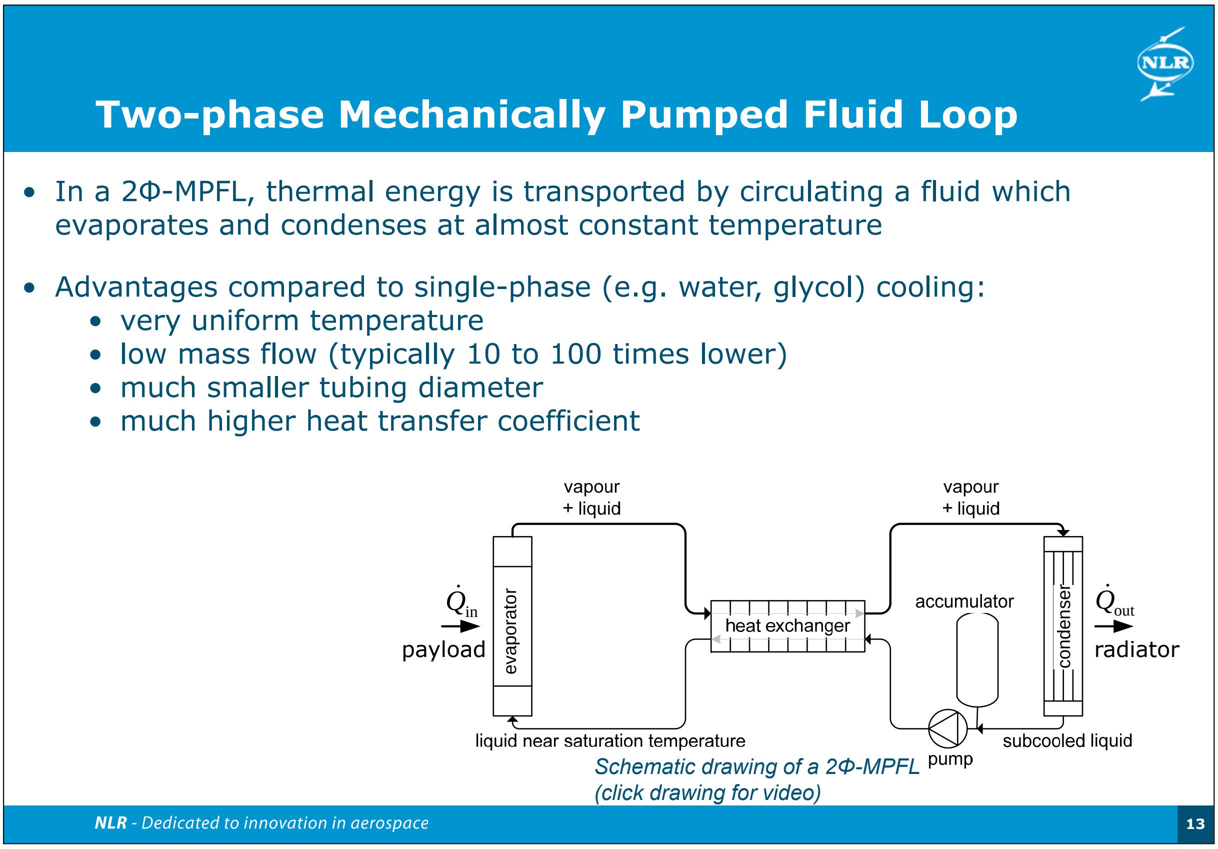
- For a Loop Heat Pipe, tl
- The major difference wi is usually dominant ove
- The flow in the vapour l
- The figure of Merit for L

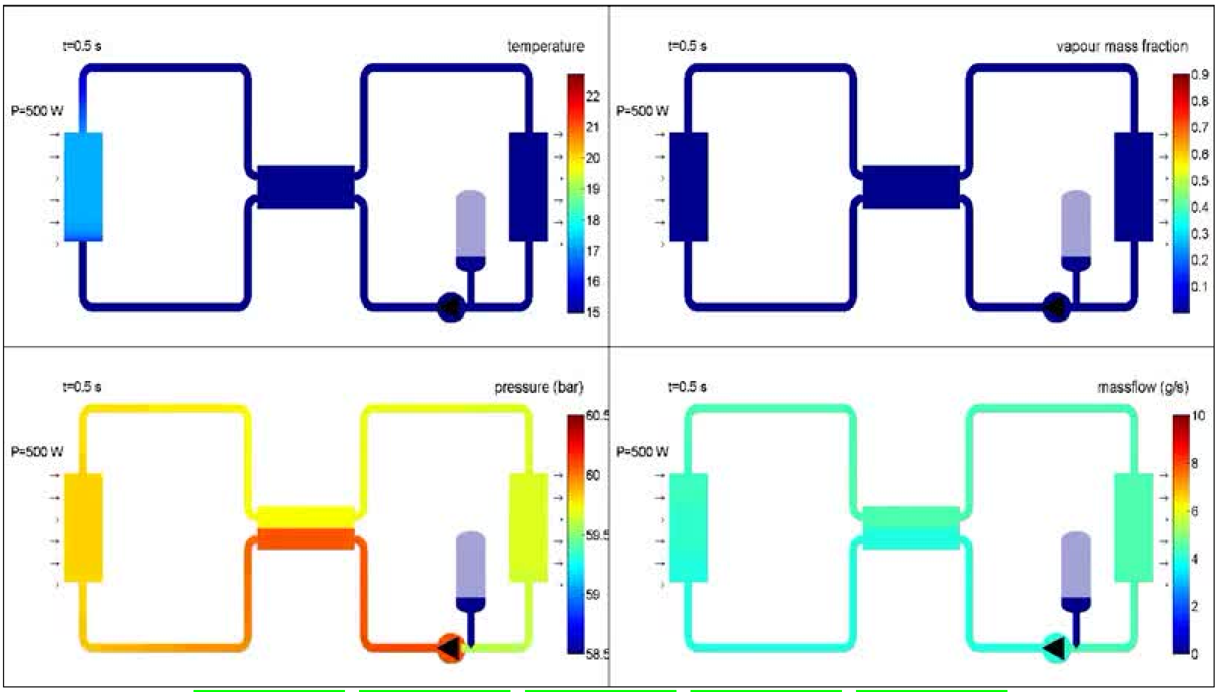
$$M = \frac{\rho_v {h_{lv}}^{7/4} \sigma}{{\mu_v}^{1/4}}$$



[1] N. Dunbar, P. Cadell, *Working fluids and Figures of Merit for CPL/LHP applications*, CPL-98 Workshop (1998)

***NLR** - Dedicated to innovation in aerospace* 10



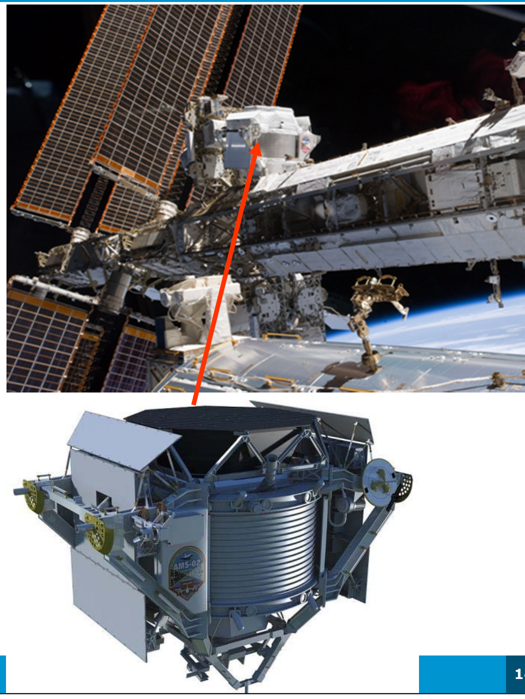


Slow Normal Fast Play/Pause Stop

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
- **So why has CO_2 been chosen as the cooling fluid?**



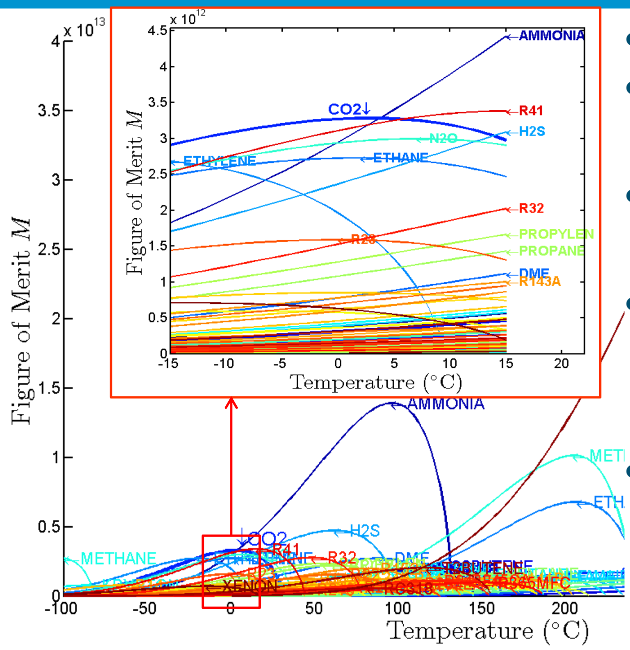
NLR - Dedicated to innovation in aerospace 14

Two-phase Mechanically Pumped Fluid Loop

- The tubing inside the tracker must have a small diameter
- However, the available pump only has a small pressure head → minimize pressure drop in the system by choosing an optimal fluid
- $$\Delta p \propto \overbrace{\left(\frac{\mu_l^{1/4}}{\rho_l h_{lv}^{7/4}} + \frac{\mu_v^{1/4}}{\rho_v h_{lv}^{7/4}} \right)}^{\text{fluid dependent}} \overbrace{\frac{L}{d^{19/4}}}^{\text{geometry dependent}} \underbrace{P^{7/4}}_{\text{heat input}}$$
- Figure of Merit based on low pressure drop is $M = 1/\Delta p_{\text{fluid dependent part}}$

NLR - Dedicated to innovation in aerospace 17

Two-phase Mechanically Pumped Fluid Loop

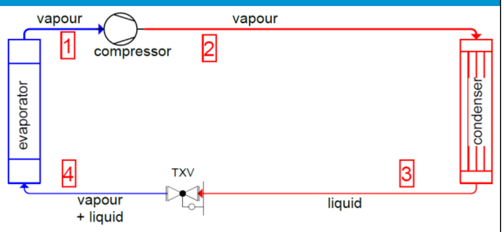


- CO_2 has the highest figure of Merit
- There are also other fluids with a similar *M*, such as ammonia, R41, N_2O, and ethane
- Some of these fluids would not have been found without the use of the figure of Merit
- After a detailed fluid trade-off, CO_2 was chosen because of low toxicity, inflammability, excellent radiation hardness and good material compatibility
- Other criteria for *M*, such as low pump power, are also possible

***NLR** - Dedicated to innovation in aerospace* 18

Heat pump

- A heat pump uses a compressor to raise the radiator temperature above the payload temperature
- This significantly increases the heat rejection capacity of the radiators

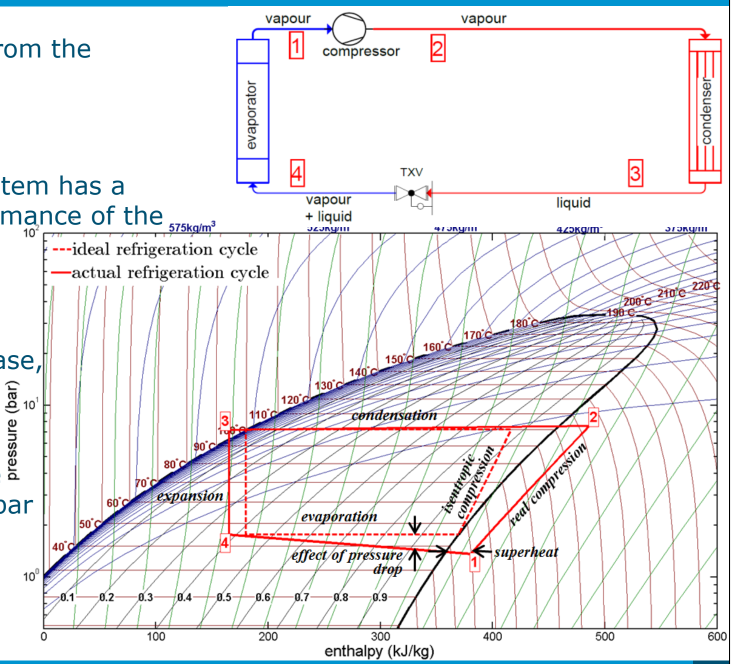


- Traditional compressors are too heavy and cause too much vibrations
- For this reason, a heat pump with a lightweight, low-vibration, high-speed (200,000 RPM) compressor has been developed in an ESA project
- The efficiency of a heat pump can be expressed with the Coefficient of Performance: $COP = P/w_{compressor}$
- So for a heat pump, the figure of Merit can be based on the COP → $M \propto COP$

***NLR** - Dedicated to innovation in aerospace* 19

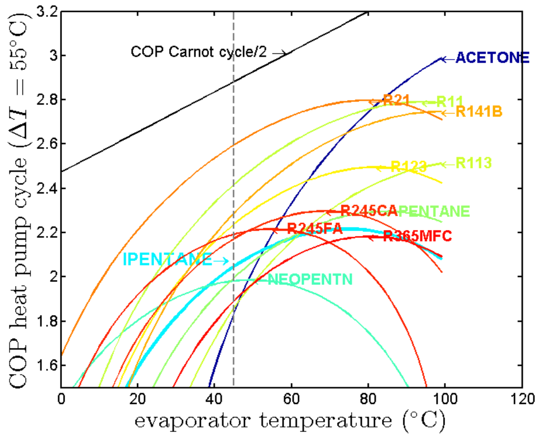
Heat pump

- The COP can be calculated from the enthalpies:
  $\text{COP}=P/W_{\text{compressor}}=\frac{h_1-h_4}{h_2-h_1}$
- The pressure drop in the system has a large influence on the performance of the system and must be taken into account
- The COP is calculated for all fluids in the REFPROP database, assuming Δp=0.4 bar and 60% compressor efficiency
- For compressor reasons, the pressure must be below 14 bar

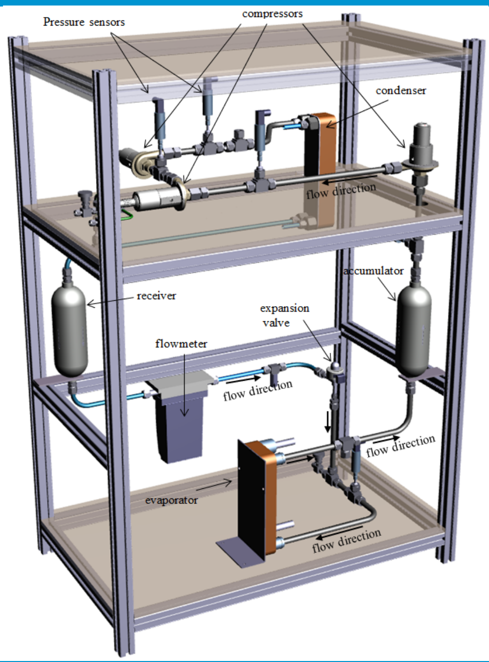


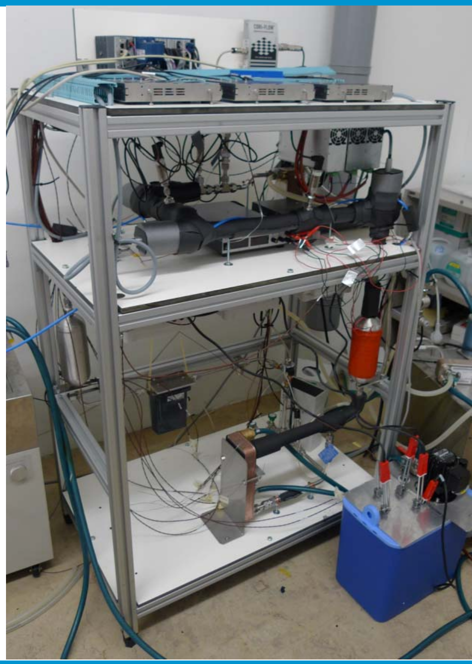
Heat pump

- The fluid selection tool shows that R21, R11, R141b, and R123 have the highest COP
- However, these fluids are banned or being phased-out according to the Montreal protocol
- The next best fluids are R245fa, R245ca, and isopentane (R601a)
- A detailed compressor analysis showed that the highest efficiency is obtained with isopentane, so this refrigerant is chosen for the heat pump application



Heat pump measurements with isopentane

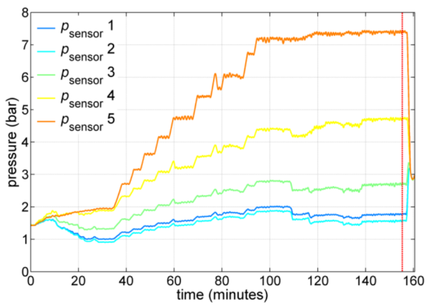


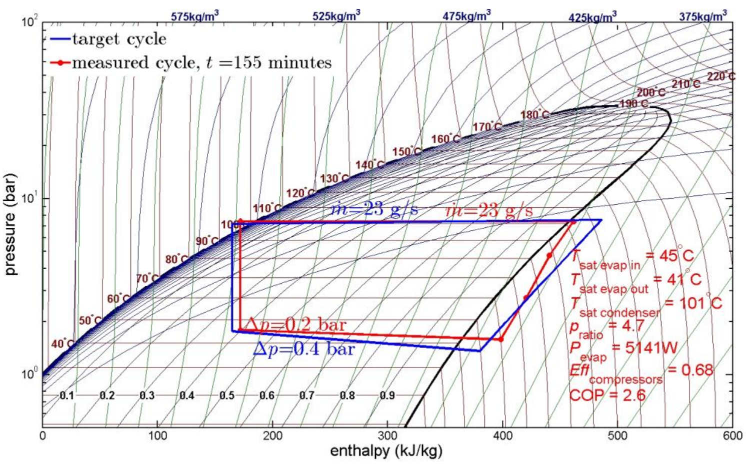


NLR - Dedicated to innovation in aerospace 22

Heat pump measurements with isopentane

- Measurements have been carried out with isopentane as refrigerant
- The measured COP is 2.6, which is considerable higher than the ESA requirement of 2



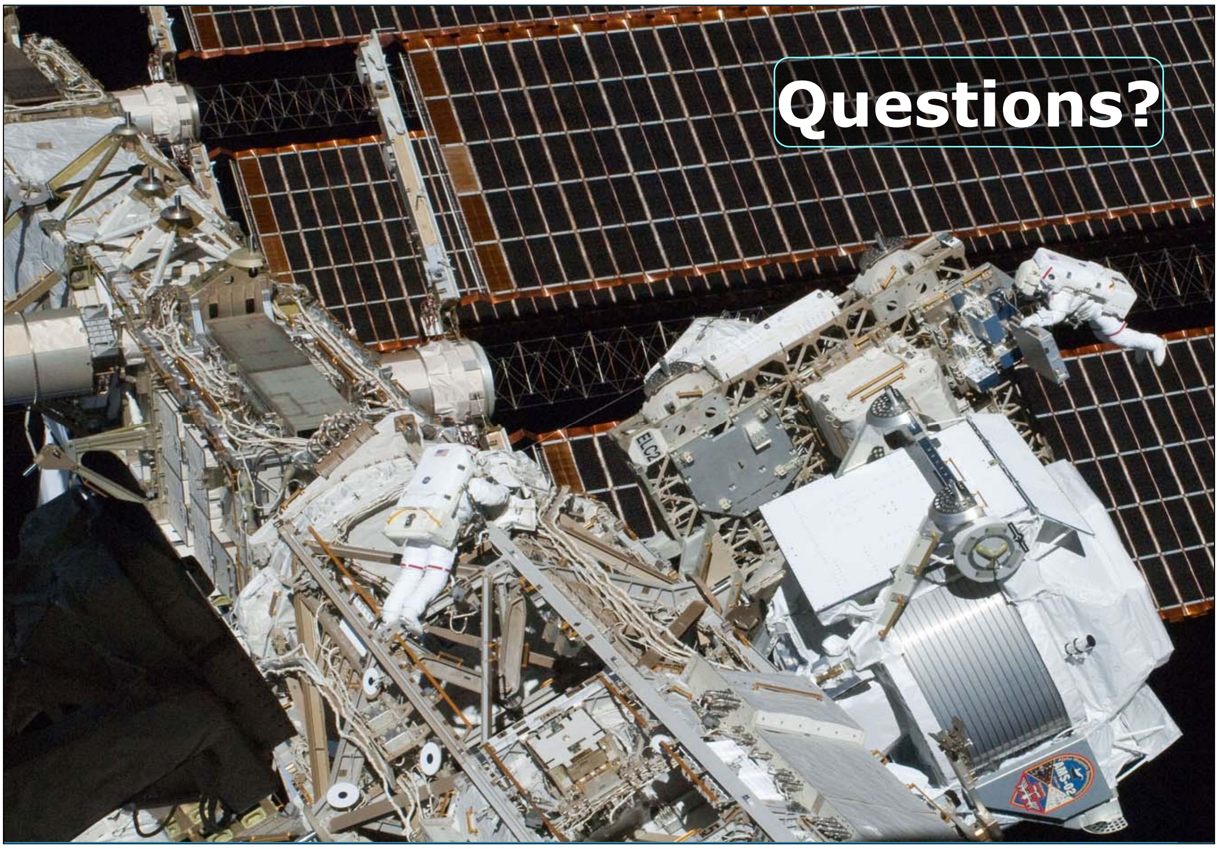


NLR - Dedicated to innovation in aerospace 23

Conclusions

- With the figure of Merit, the most suitable fluids are selected from the REFPROP database for a wide range of applications
- With this systematic approach, fluids can be selected which otherwise would have been overlooked
- The use of the figure of Merit is implemented in a fluid selection tool
- With this fluid selection tool, the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button

NLR - Dedicated to innovation in aerospace 24




Dedicated to innovation in aerospace
DEFENSE & PEACEKEEPING MISSIONS
INNOVATION
JOB CREATION
MOBILITY
SAFETY
ENVIRONMENT
www.nlr.nl - info@nlr.nl