Czech Technical University in Prague
Faculty of Mechanical Engineering
Department of Applied Physics
Technicka 4, 166 07 Praha 6,
Czech Republic
tel./fax.: 3113657

Problems in design of cooling systems for particle detectors and relevant electronics

Vaclav VACEK

Scope of the presentation:

- Background of our research activities
- Overview of our participation in the projects
- Overview of the problems faced during the last 25 years of development work
- Two recent interesting use cases dealing with **lower power dissipation tasks**
  - Enhancing the Cooling Power of the AIRCOOLER devices
  - Versatile Cooling Circuit (TOTEM Project at H8) – test of evaporators with metal foam fillers
- Summary and conclusion remarks

Background of our research activities

- Our team has been involved for more than 25 years in design and development of the cooling system suited for the particle detectors located distributed along the LHC at CERN

- Our projects are dedicated to the particle detector cooling matters @ medium temperatures, ie. from room temperatures down to -55ºC

- Our experience span from:
  - Monophase liquid cooling system (fluorocarbon liquids, even water solution, some in leak-less systems)

  up to
  - Evaporative cooling systems (= vapor compression systems) (mainly with fluorocarbon fluid, some with CO_2), both with powers ranging from tens W to 70 kW

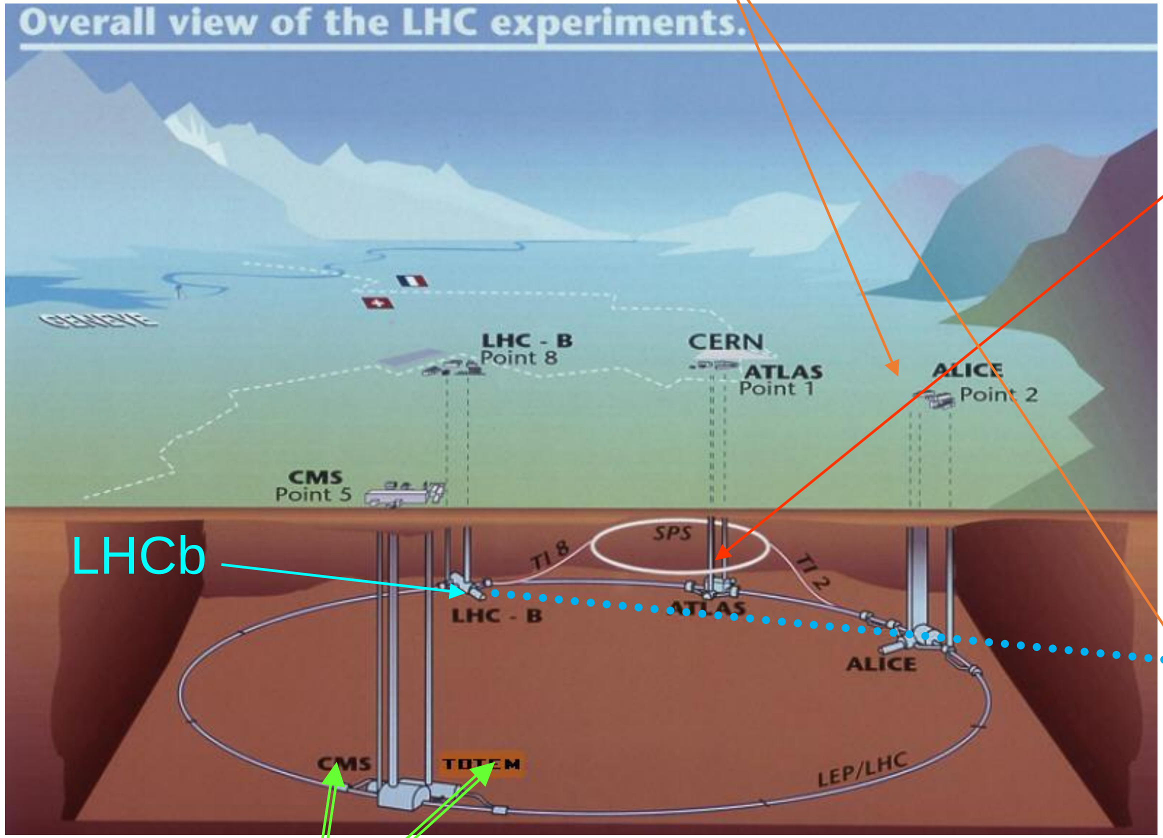
  and even with
  - Air cooling devices designed for the low power dissipations up to few hundreds W

Overview of our participation in the projects

ALICE (R610/C_4F_{10})

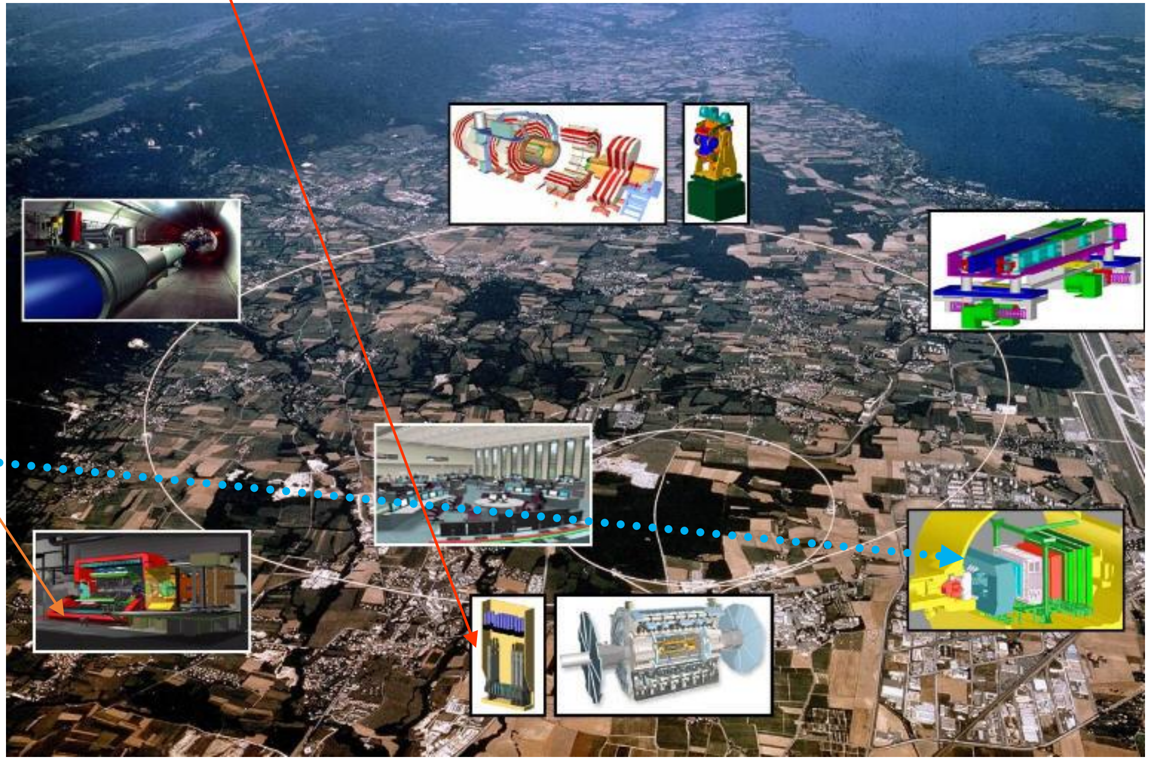
ATLAS (R218/C_3F_8)

ATLAS AFP (Air)



LHCb

TOTEM (R218/C_3F_8) around CMS



Overview of the problems faced during the development work

Major differences that one has to consider in these applications compared to the standard refrigeration installations

- We are cooling down unique and extremely expensive high-tech electronics that will not be possible to replace if some damage or failure of the cooling system occurs
- Floating required specification during the design period and construction process
- All parts must be continuously cooled and maintained at the required temperature over the lifetime of the experiment (COP ??? not strictly priority …, different detector zones call for temperature neutral solutions)
- A lot of the experience and standard parts known in the refrigeration industry are excluded due to the working environment (radiation and strong magnetic field)
- Green refrigerants and heat transfer fluids (with low GWP) are not radiation hard in general. Flammable fluids are immediately excluded (underground areas …)
- Aspects of dielectric properties and chemical stability of refrigerants are vitally important
- Evaporator tubes are often also supporting elements for the delicate and very expensive detector electronics
- Space constrains and limited accessibility inside of the detectors structure
- Thermal interference with other detector sections is to be minimized
- Missing information about important thermophysical properties of the relevant radiation-hard fluids and mixtures used in this field

What may help to cope with challenges

Some hints:

- Great courage and endless tolerance
- Solid information and knowledge about thermophysical properties of relevant fluids (fluoroinert/fluorocarbon family, CO_2 and others).
- Use of the simulation models whenever possible and add solid and critical comparison with experimental results.
- Background for the tests require reliable DAQ systems including sensors, and detailed commissioning and verifications of all key components is the “must”.
- Careful scaling up of the cooling system set-up, some small-scale mock up systems should be constructed and commissioned prior to the full-scale system realization.
- Developing of a tailored system is often the only solution.

What we can offer:

- Data about the most fluorocarbons, derived both via semi-empirical approach and simulation (SAFT EOS, MC and MD simulations).
- Two phase capillary flow simulation model are available (including contamination impact).
- Many experimental cooling circuits were prepared and used both as prototypes and final design structures.

Two recent interesting use cases

Both presented use cases are dealing with lower energy dissipation (cooling power) with great potential for many different applications in electronics cooling

The first use case deals with AIRCOOLER units (developed by us) use.

- The system is currently deployed and works for detectors with dissipation powers up to hundred watts.
- It is in use for small detectors of RP type within the AFP (Atlas Forward Physics) experiment (*4 units serving without problems/failures for 4 years in the LHC Tunnel*)

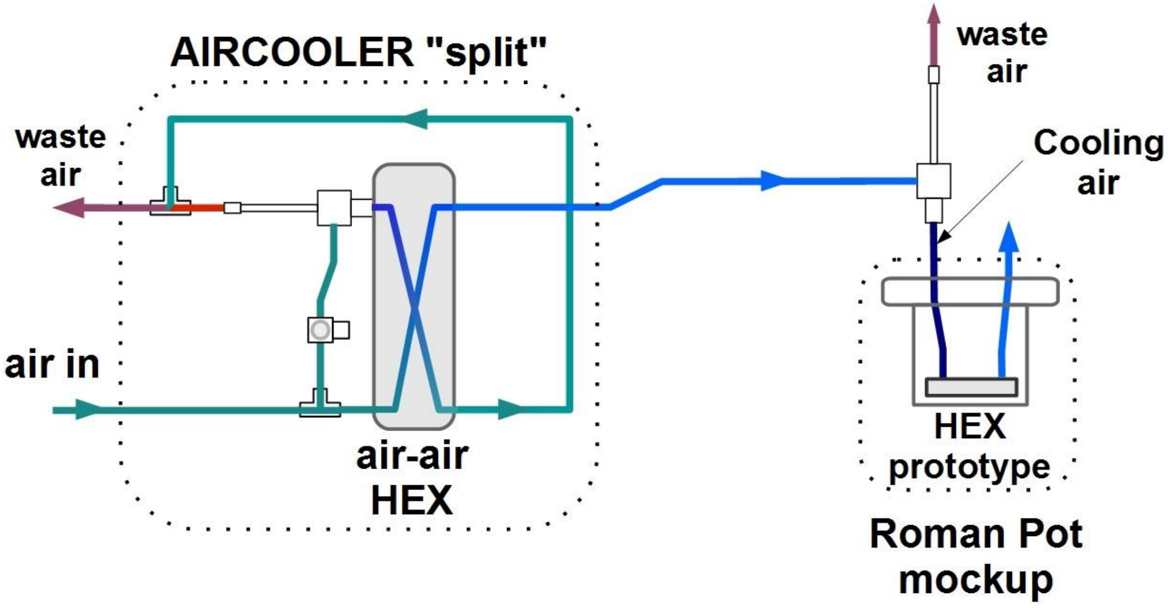
The second use case presents evaporative cooling system with the cooling power around 1.5 kW

- Serving primarily for commissioning of the various types of RP detectors (both silicon and diamond types) for the TOTEM experiment
- Circuit has a great variability in setting up the running conditions and it is suited to accept various refrigerants and even mixtures
- It allows non-insulated lines due to the effective compact heat exchanger placed after the evaporator (eliminates effectively use of additional electrical heaters ….)

The first use case - AIRCOOLER unit (developed at CTU) in use

We have developed three types of units up to production lines called AIRCOOLERS (widely published elsewhere)

- Widely used model in the LHC tunnel - the AIRCOOLER_Split (the ACS)



Main advantages:

- No moving parts, no electricity needed
- Air as the working fluid
- Low sensitivity to the leaks
- Fixed setting with no control system requirements possible
- Maintenance free device

Limitations:

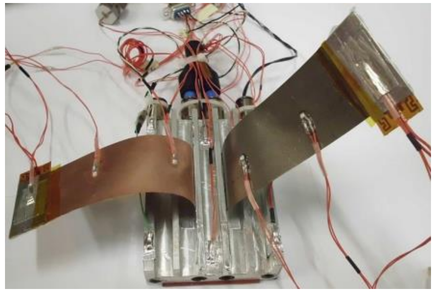
- Limited pressure available (safety issues)
- Low overall efficiency – OK for low power dissipations

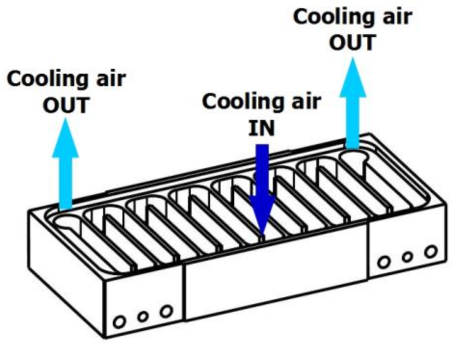
- The main pre-precooling box reduces the air temperature in the first stage to a moderate temperature and an additional connected single vortex tube cools the air down to the required level in the second stage
- The integration of the second vortex tube in to the flange of cooled object improves process efficiency and lowers airflow temperature down significantly
- The heat exchanger performance has its limits

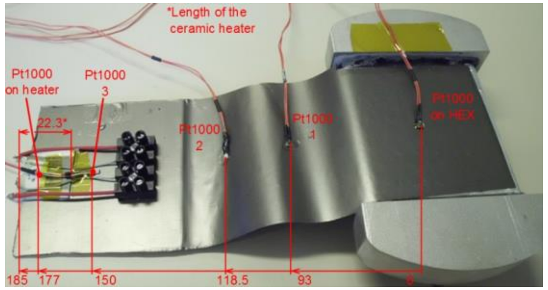
$$\dot{q} = \alpha \cdot A\,(t_w - t_{air})$$

The first use case - AIRCOOLER unit – performance enhacement

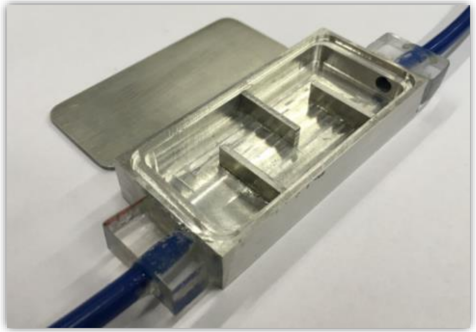
- The heat transfer can be enhanced by roughening the inner surface or introducing inner fins inside the heat exchanger, both interventions being problematic
- We have tested various heat exchangers configurations (with inner surface expansion), including usage of Cu and PGS foils to enhance heat transfer from heat sources to heat exchanger surface

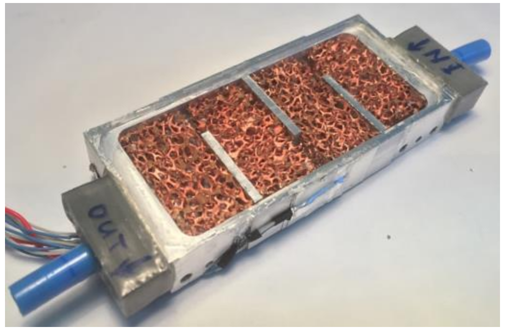


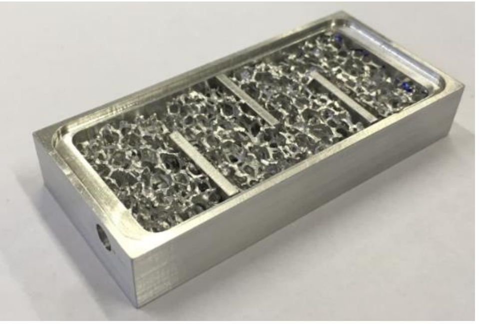




- The best results we have obtained with metal foam fillers



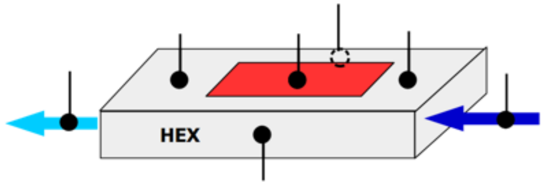


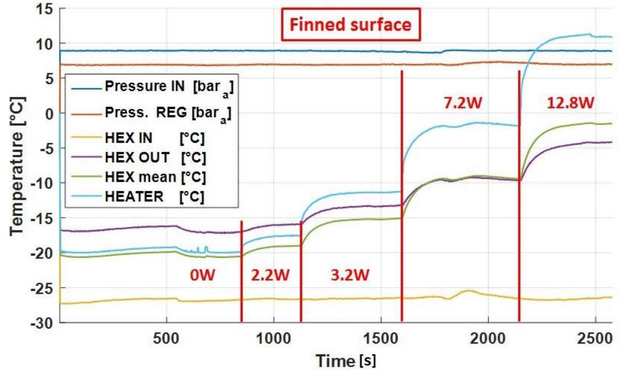


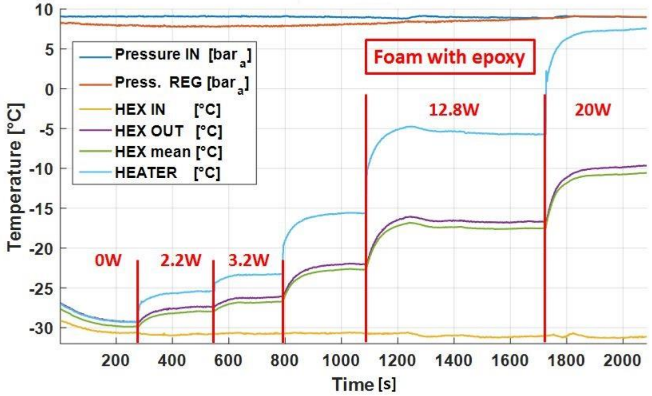
Various implementations with
- Cu (porosity of 91 %) and
- Al (porosity of 93 %)

foams were selected for our tests (plain foams and foams treated with thermally conductive paste)

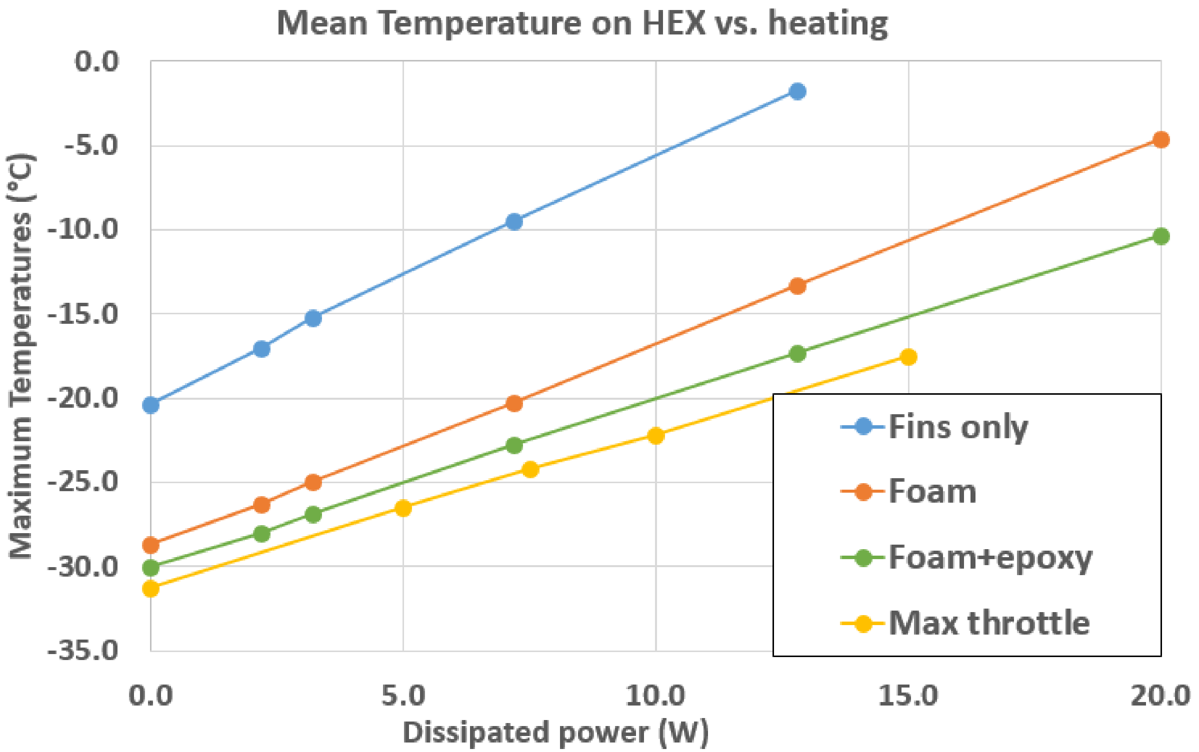
The first use case - AIRCOOLER unit – performance enhacement





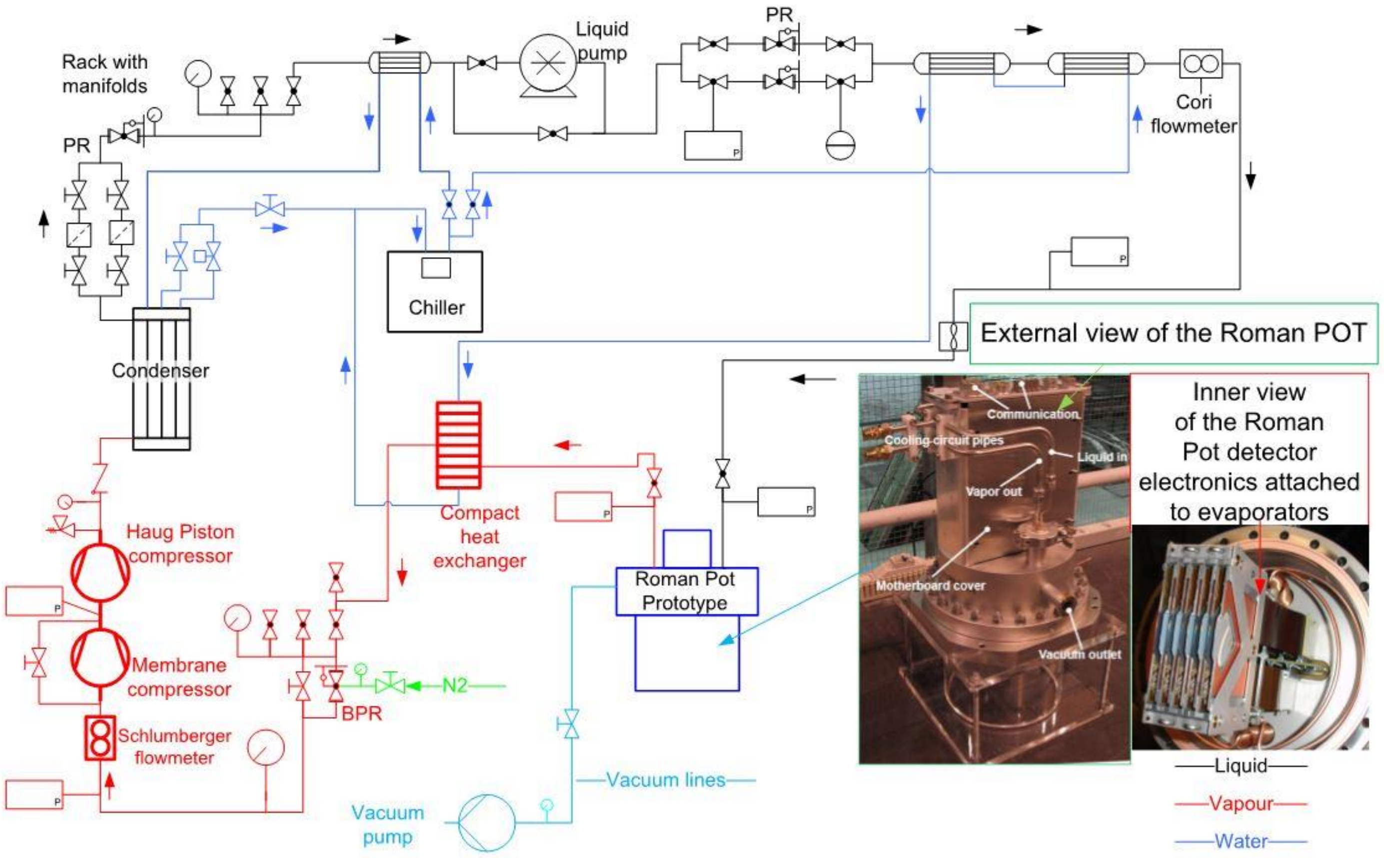


Each different heat exchanger design under investigation has been tested under the same conditions, i.e. with the same nominal input pressure of 8bar into the AIRCOOLER I and cooling air temperature at the inlet into the heat exchanger around -25° C.



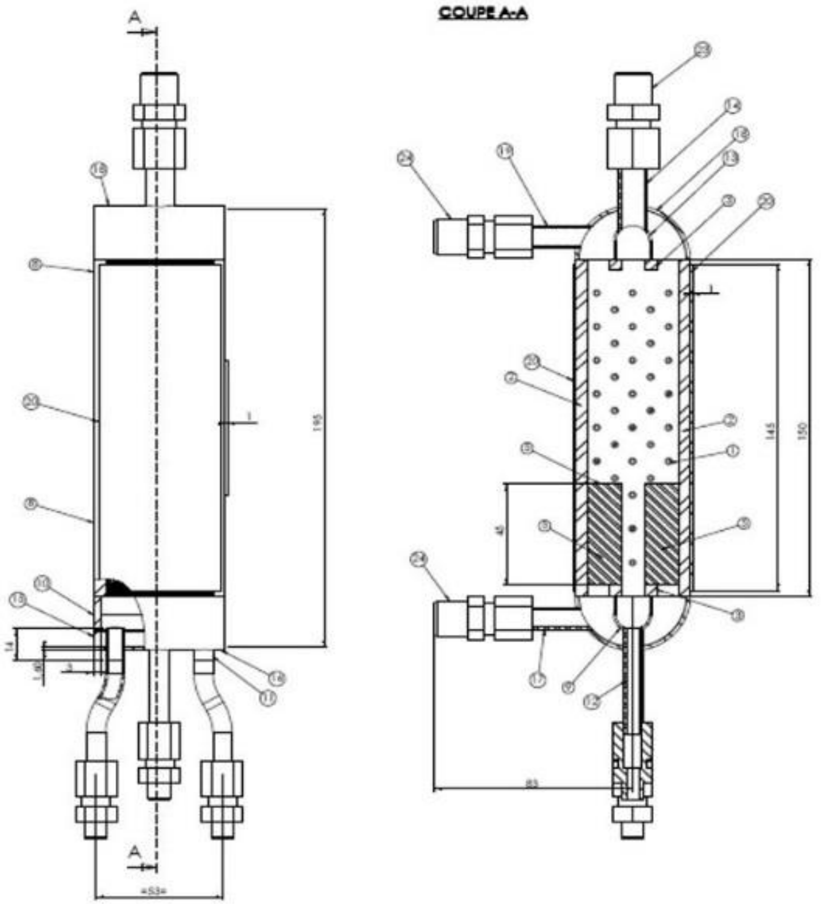
Comparisons of results between finned surface and foam extended one; temperatures were down by approx. 10° C

The second use case - versatile cooling circuit for fluorocarbons



- Circuit comprises two oil-free compressor units (to cover refrigerant mass flow in the range of 1 to 9 g/s).
- Tested with the fluorocarbon refrigerant R218 and fluorocarbons mixtures (R218 and R116). The use of refrigerants R-404A, R-452A and R-449A was also successfully tested.
- A DAQ system based on ELMB technology is connected by CANBUS to a PC screening over 25 sensors of different type around the cooling circuit.
- Some from 50 to 70 extra sensors possible to add
- A special attention has been devoted to preventing insulation around the exhaust vapour lines and at the same time to make sure that no condensation takes place on the surface of those lines.
- Single water/vapour compact heat exchanger handles the cold vapour

The second use case - versatile cooling circuit for fluorocarbons

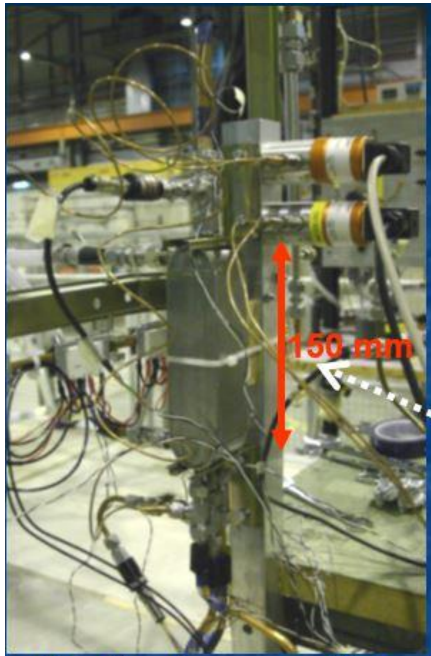


- The device (replacing traditional heaters) allows increase of vapour temperature (by 50°C) over the short distance (150mm) while still keeping pressure drop of vapour section at relatively small values (less than 10kPa).

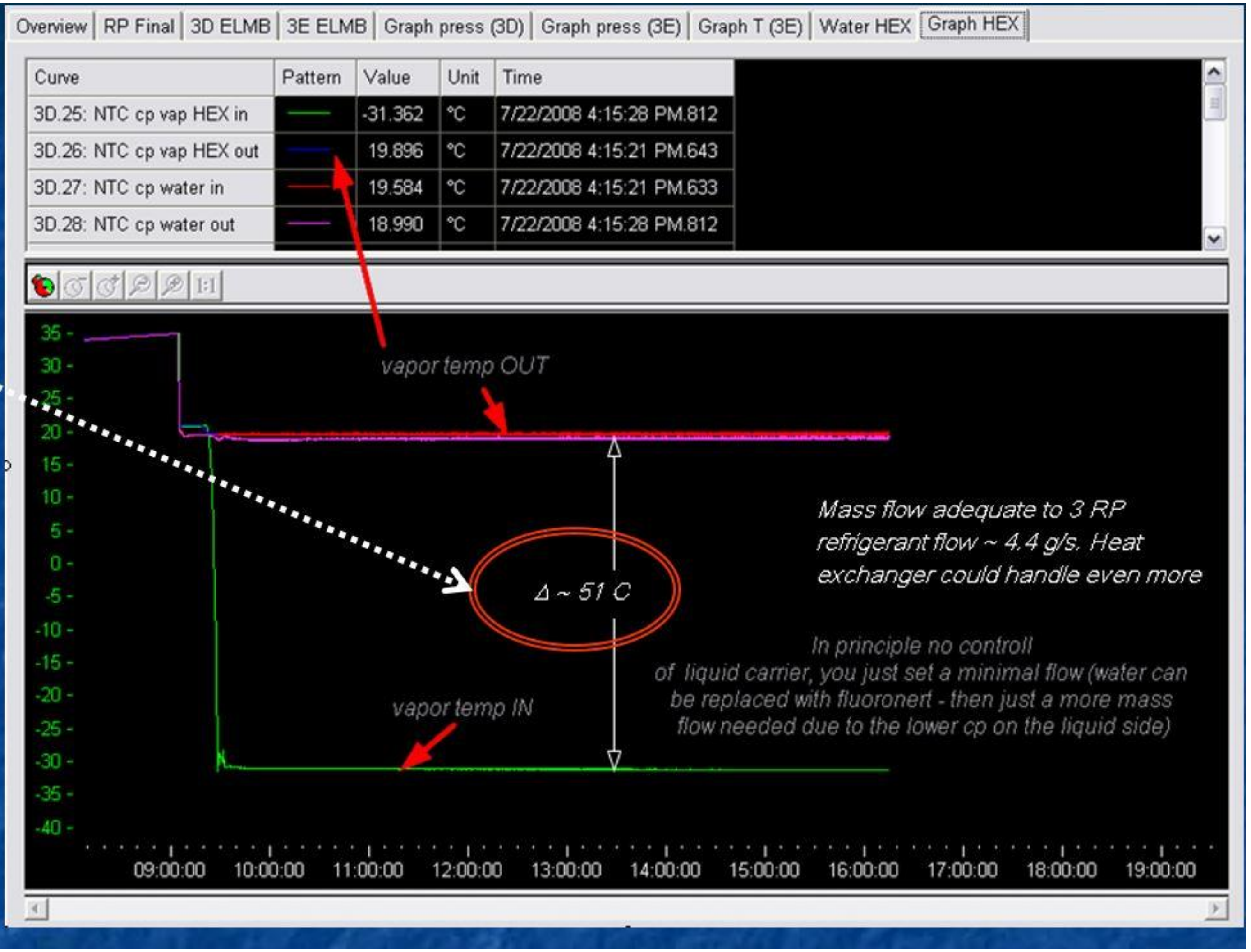
- It also turned out that search for minimal required flow of water (6 cm^3.s^{-1} at vapour flow up to 5g.s^{-1} @ -30ºC) passing through and keeping still fully functioning heat exchanger makes it a self-tuning unit which does not need any additional control system.

- Moreover, since both fluids are separated by stainless steel there is no need to tackle problems with compatibility of the refrigerant and sensitive elements of the heaters, seals around wires, and there is no need for an expensive control system

The second use case - versatile cooling circuit for fluorocarbons



It is clearly more efficient solution of the surface tube condensation problem compared to the frequently used additional electrical heater system inside or around exhaust vapour lines.



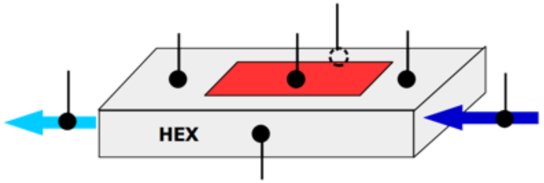
Curve	Pattern	Value	Unit	Time
3D.25: NTC cp vap HEX in	🟩	-31.362	°C	7/22/2008 4:15:28 PM.812
3D.26: NTC cp vap HEX out	🟦	19.896	°C	7/22/2008 4:15:21 PM.643
3D.27: NTC cp water in	🟥	19.584	°C	7/22/2008 4:15:21 PM.633
3D.28: NTC cp water out	🟪	18.990	°C	7/22/2008 4:15:28 PM.812

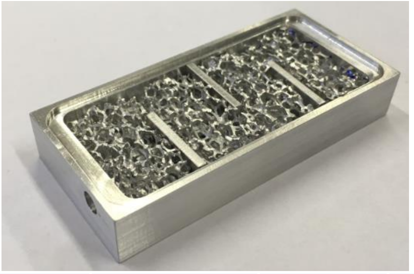
Mass flow adequate to 3 RP refrigerant flow ~ 4.4 g/s. Heat exchanger could handle even more

In principle no controll of liquid carrier, you just set a minimal flow (water can be replaced with fluoronert - then just a more mass flow needed due to the lower cp on the liquid side)

Photo of the employed HEX and Screenshot showing the proof of HEX efficiency

The second use case - versatile cooling circuit for fluorocarbons





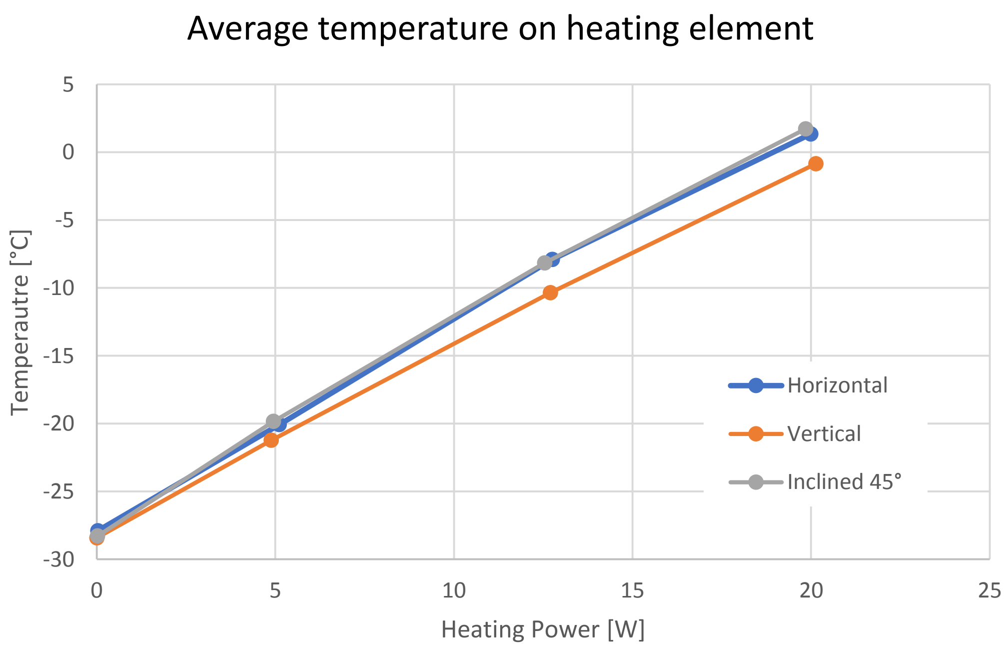
We have tested the use of the metal foam also inside the evaporative heat exchangers at H8. Size corresponds to the size of one evaporator in the old RP and it has an outer shape of the HEX used for air cooler

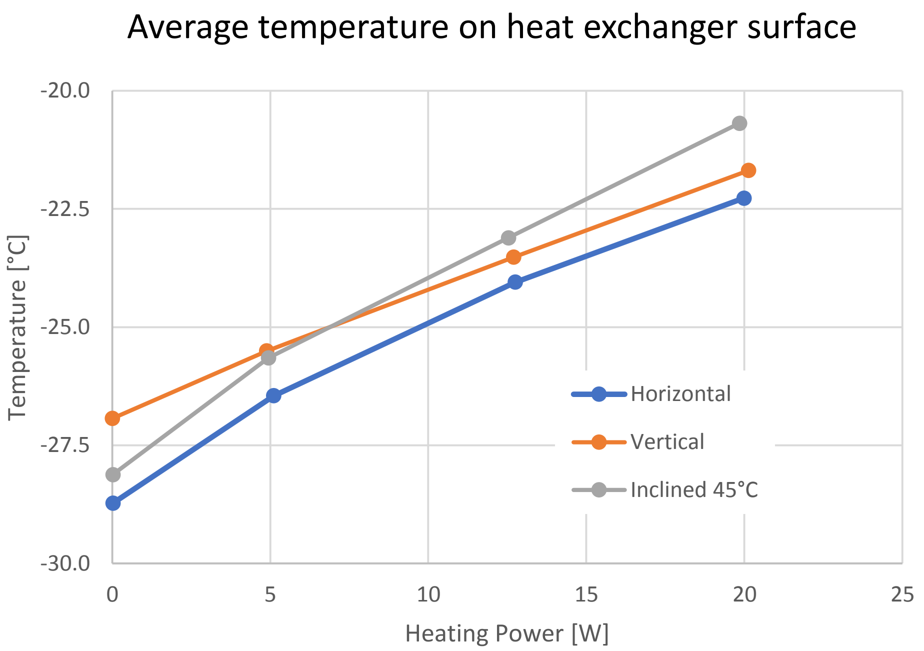
Three position were analyzed:

- Horizontal
- Vertical
- inclined

	Date/Description		Liquid	Liquid			Availale	Outlet	Average Surface	Min Surface	Max Surface	
		Power	Temp	pressure	Liquid enthalpy	Vapor enthalpy	Enthalpy	Quality	Temp	Temp	Temp	CORI mass
		W	C	bara	J/g	J/g			C	C	C	g/s
Vertical	0V	0,0	19,5	9,75	221,5	271,5	32,1	0,00	-26,9	-29,6	-20,3	0,64
Vertical	5V	4,9	19,5	9,74	221,5	271,5	35,0	0,14	-25,5	-27,8	-19,9	0,70
Vertical	8V	12,7	19,5	9,73	221,5	271,5	32,8	0,39	-23,5	-25,6	-18,7	0,66
Vertical	10V	20,1	19,5	9,73	221,5	271,5	34,1	0,59	-21,7	-24,2	-17,6	0,68
Vertical	5V	4,9	19,5	9,71	221,5	271,5	34,7	0,14	-25,5	-27,9	-20,1	0,69
Vertical	0V	0,0	19,5	9,43	221,6	271,5	30,8	0,00	-26,9	-29,3	-21,0	0,62
Horizontal	0V	0,0	19,5	9,53	221,5	271,2	33,8	0,00	-28,7	-30,3	-26,7	0,68
Horizontal	5V	5,1	19,5	9,60	221,5	271,4	34,4	0,15	-26,5	-27,7	-25,2	0,69
Horizontal	8V	12,7	19,5	9,64	221,5	271,2	34,4	0,37	-24,0	-25,9	-22,5	0,69
Horizontal	10V	20,0	19,5	9,66	221,5	271,3	34,6	0,58	-22,3	-25,0	-19,9	0,70
45°	0V	0,0	19,5	9,63	221,5	271,2	34,2	0,00	-28,1	-30,0	-26,7	0,69
45°	5V	4,9	19,5	9,62	221,5	271,2	34,0	0,15	-25,6	-26,9	-24,7	0,68
45°	8V	12,5	19,5	9,61	221,5	271,2	33,9	0,37	-23,1	-24,5	-21,9	0,68
45°	10V	19,8	19,5	9,61	221,5	271,2	33,6	0,59	-20,7	-23,8	-18,3	0,68

The second use case - versatile cooling circuit for fluorocarbons





- We are able to cool down by single HEX (ie. it correspond to one half of the current evaporator inside the RP) up 15 W not seeing dry out.
- It means that theoretically, having the both sides inside the RP filled with two new evaporators we could evacuate up to 30 W from a single POT and it is much, much more than needed
- At the same time we have nearly no pressure drop over the evaporator, so our evaporation temperature does not display any glide, so it gives us uniform temperature on all surfaces of the cooled block and we see those surfaces around -27 C or lower.
- Mass flow is reduced by 40% compared to the old arrangement, ie. to take the same amount of heat away.
- Cooperation with board designers is needed to utilise these nice results.

Summary and concluding remarks

- I have pointed out very frequent problems and obstacles that one will meet in this specific field
- I have also summarized the research procedures that might be useful (Mathematical modelling and simulation) in reduction of the experimental phase of development
- Two interesting solutions were demonstrated via two use cases supported by experimental results:

  - 1st Use case
    - Use of AirCooler devices for High-Tech electronics
    - Improvement of the heat exchanger (gas/solid) performance thanks to the metal foams application
  - 2nd Use case
    - Development of the versatile and flexible CS for wide spectrum of refrigerant and refrigerant mixtures
    - Elimination of the electrical heaters through the effective compact heat exchanger (water/vapour type)
    - New experimental campaign: modifications of the evaporators filled with metal foams

Thank you for your kind attention!!!

Any Questions ???