Development of a Cooling System for GAPS using Oscillating Heat Pipe

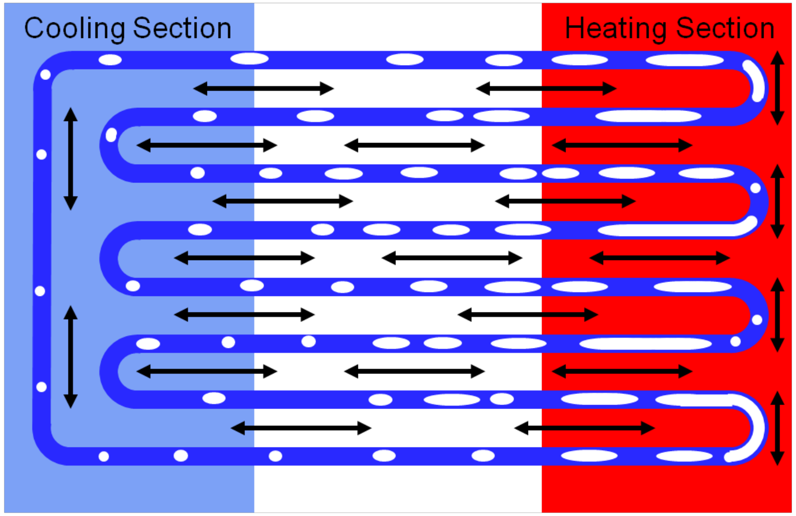
Hideyuki Fuke

(JAXA/ISAS)

on behalf of the GAPS collaboration

Oscillating Heat Pipe (OHP)

- OHP is a new technology of thermal engineering.
  OHP was invented by a Japanese engineer at a small company in 1990's.
- OHP consists of meandering capillary tube going back and forth between the heating section and the cooling section.
- Working fluid is encapsulated in the tube as gas-liquid two-phase flow. Vapor bubbles generate in the heating section and condense in the cooling section. The pressure and temperature fluctuations due to this phase change cause the self-oscillation that transfer heat passively both by sensible and latent heat.

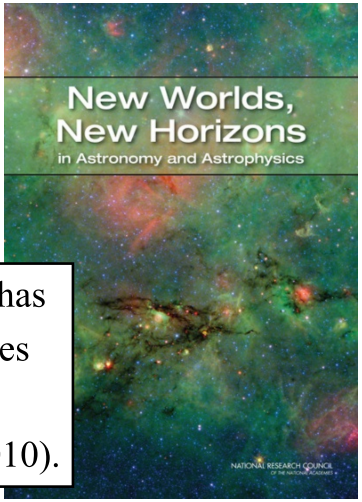


GAPS Project

- General Anti-Particle Spectrometer (GAPS) is an international astro-particle project aiming to contribute to solve the dark matter mystery through highly sensitive observation of cosmic-ray antiparticles, especially unexplored anti-deuterons.
- To achieve a high sensitivity with suppressing the effect of the geomagnetic cutoff, GAPS plans its first Antarctic LDB flight in around 2020.

Dark matter physics is one of the most important topics of the 21st century physics and is an explicit goal of the NASA 2014 Science Plan.

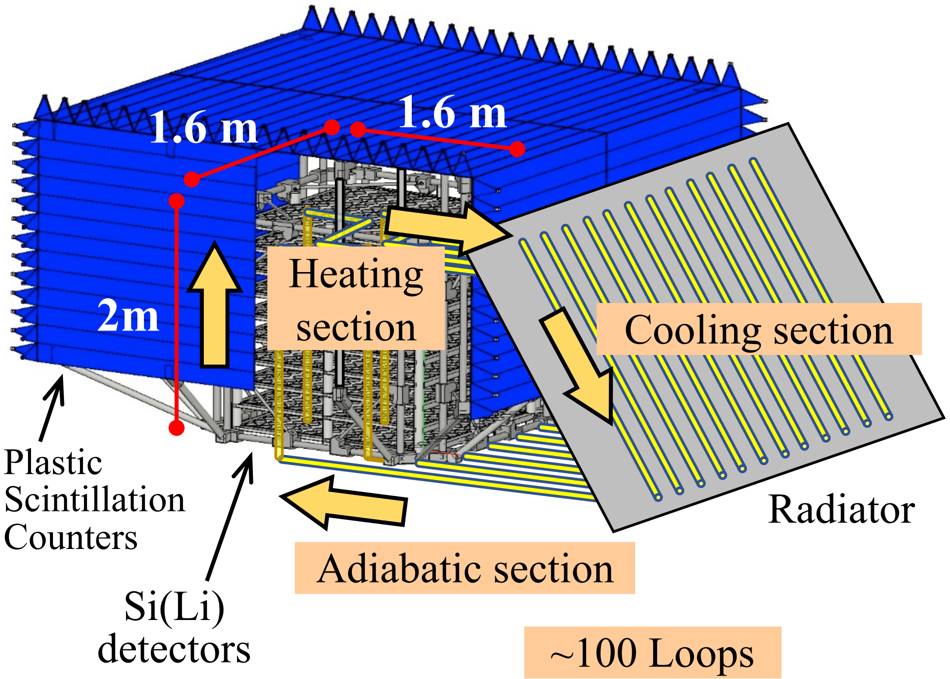
The significance of the GAPS physics has been recognized by science communities as discussed by the Astronomy and Astrophysics Decadal Survey (Astro2010).



- Development of the detector cooling system is vital for GAPS;
  Plenty of (~ 1300) core silicon detectors must be cooled all at once. The total amount of heat dissipation is large but the heat sources are spread over a wide space. The detectors should be cooled down to ~ -35°C with limited power and mass resources.
- Oscillating Heat Pipe (OHP) is an attractive candidate to meet the requirements for the GAPS cooling system.

Requirements for Cooling System

- Heat source:
  - Large amount of heat (total heat dissipation ~< 140 W). (*c.f.* max. 800W)
  - Low heat flux (spread over a wide area ~ 1.6m × 1.6m × 2m).
  - The silicon detectors to be cooled down to lower than -35^{o}C.
- Heat transfer route:
  - Transport heat to a radiator at the payload sidewall (~> 2 m apart).
  - $\Delta T < 10^{o}C$ (small T gradient) (assuming radiator ~ -50^{o}C).
  - Winding transfer route (transferring under gravity).
- Antarctic balloon flight:
  - Gravity.
  - Large input heat flux (midnight sun, intense albedo from ice).
  - Low power consumption, light-weight.



Oscillating Heat Pipe (OHP)

- Advantages of OHP:
  - Simple fabrication. No need for internal wick.
  - Lower sensitivity to gravity than conventional HP.
  - Capable to transfer large amount of heat.
  - Adjustable to low heat flux.
  - **No need for electric power** in principle.
  - Temperature controllable by using liquid reservoir.

Method	Gravity	Spread Low Heat Flux	Thin Pipe	Electric Power	**Total**
Normal Heat Pipe	×	◎	○	◎	×
Loop Heat Pipe	○	×	○	◎	×
Closed Loop with Pump	○	○	○	△	○
OHP	○	○	◎	◎	◎

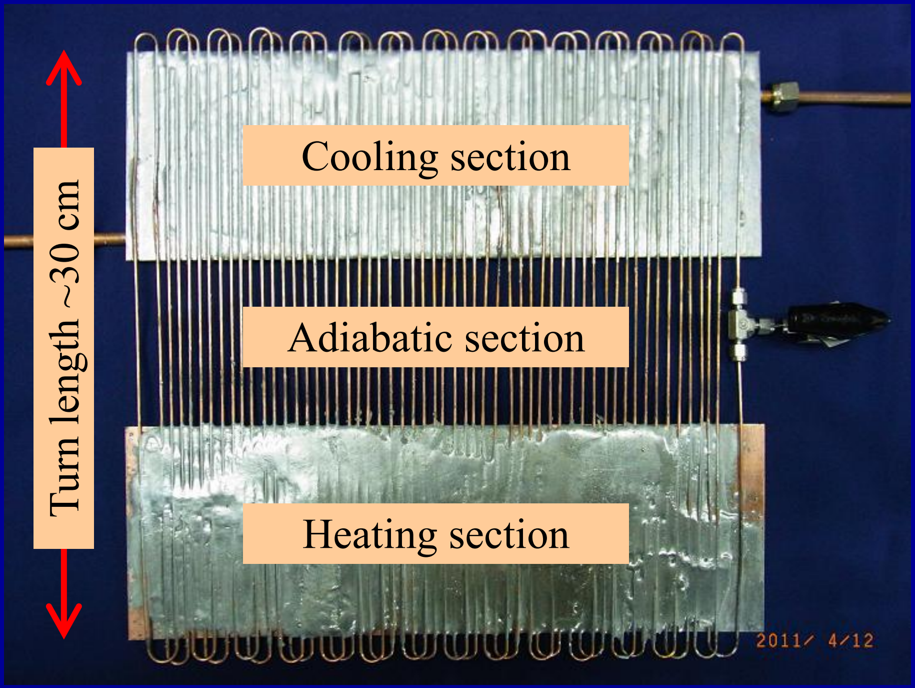
Oscillating Heat Pipe (OHP)

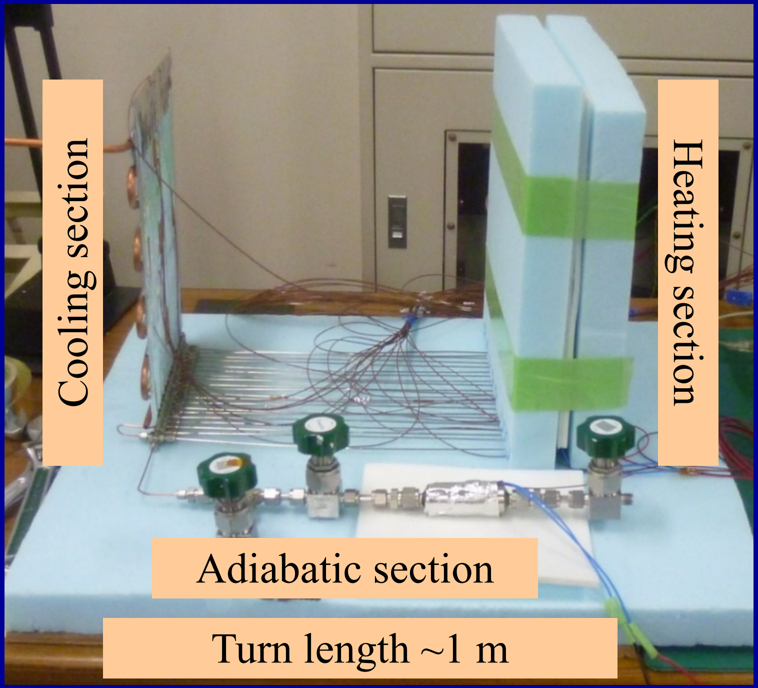
- Because the concept of OHP is new,
  the OHP has never been utilized in practical use
  neither for a spacecraft nor for a balloon-craft.
- The OHP had been researched mainly to
  understand its fundamental phenomena.
  Therefore, most of the OHPs studied in the past
  were desktop-scaled less than 1 m with planar
  routing and were operated at room temperature.

- For GAPS, we have to develop an OHP with the following features:
  - Turn length of several meters.
  - 3D complex heat-transfer routing.
  - Wide operational temperature range of -50^{o}C ~ +20^{o}C
    (especially suitability to low T).

Initial Studies with scaled-down OHP

- Selection of working fluid material for T ~ -40^{o}C:
  - R410A (most prospective), R23 (under investigation), *c.f.* R134a (low VP), CO_2 (narrow T range), NH_3 (hazardous).
- Three dimensional routing:
  - "U-shaped" OHP with ~1m turn length operated at T ~ -50^{o}C – +25^{o}C.
  - Design studies about layout of check valve, reservoir, insulator, etc.





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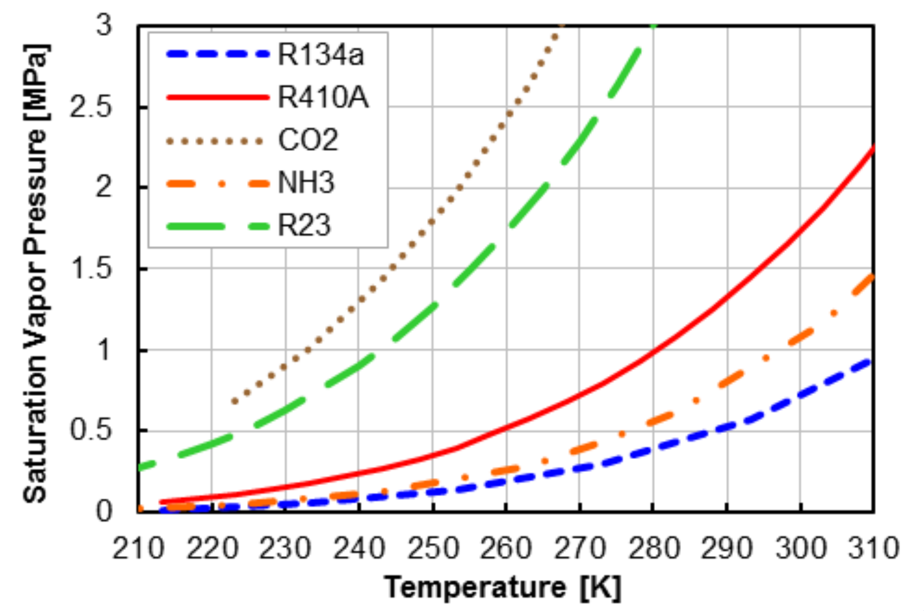
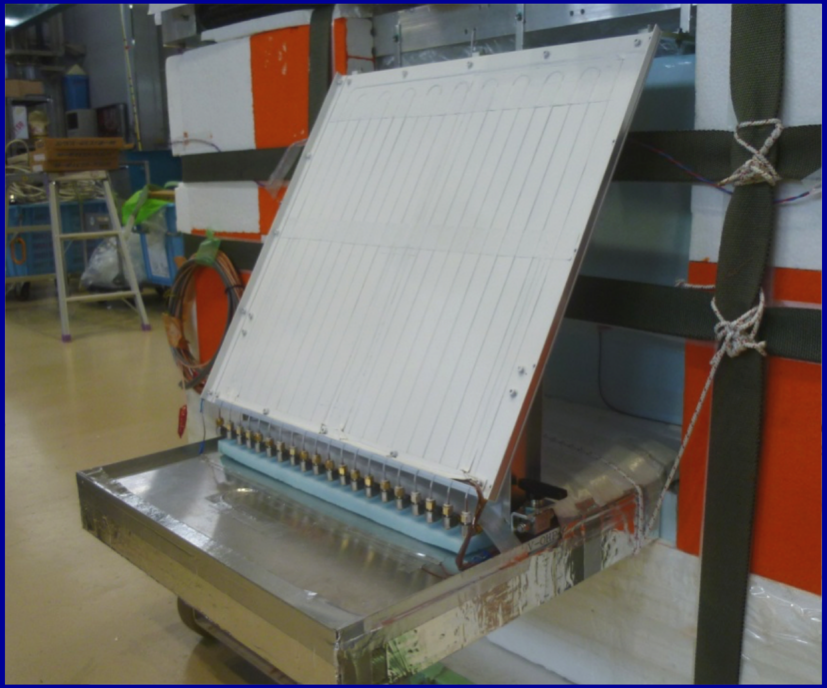
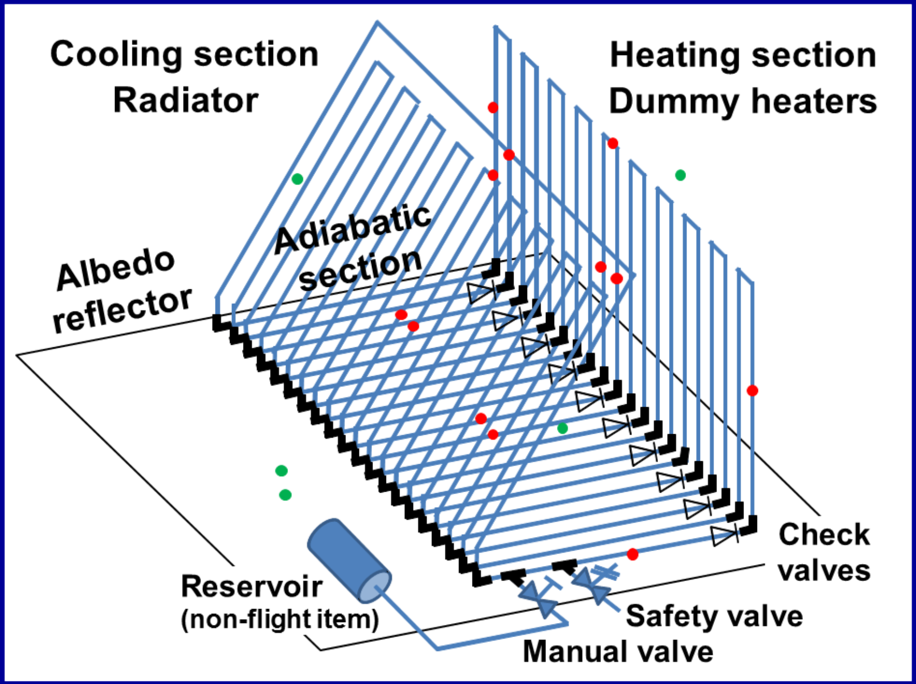
Material	Formula	Remarks
R134a	CH_2FCF_3	1,1,1,2-Tetrafluoroethane. Hydrofluorocarbon.
R410A	CH_2F_2 / CHF_2CF_3	50% / 50% mixture of R32 and R125. Hydrofluorocarbon.
Carbon dioxide	CO_2	Triple point temperature 216.6 K. Critical temperature 304.2 K.
Ammonia	NH_3	Short exposure can cause serious health hazard.
R23	CHF_3	Trifluoromethane. Hydrofluorocarbon. Critical temperature 299.1 K.



Flight Demonstration of OHP (1)

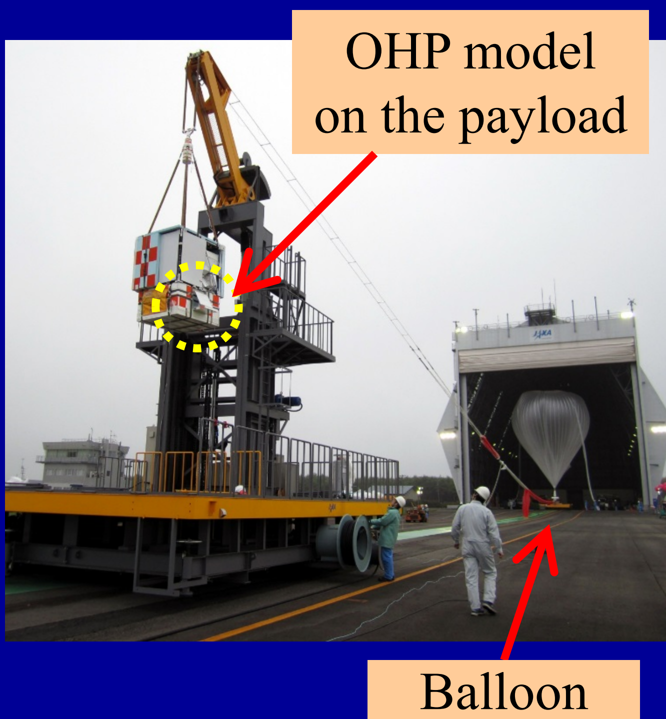
- A scaled-down OHP was evaluated through an engineering balloon flight.
  - U-shaped, 10 turns, turn length ~ 1m.
- System design for an actual flight.
  - Radiator panel, albedo reflector, safety gears.
- Stand-alone evaluation with heater ON/OFF commands.
  - Thermally & electrically isolated from other onboard subsystems.

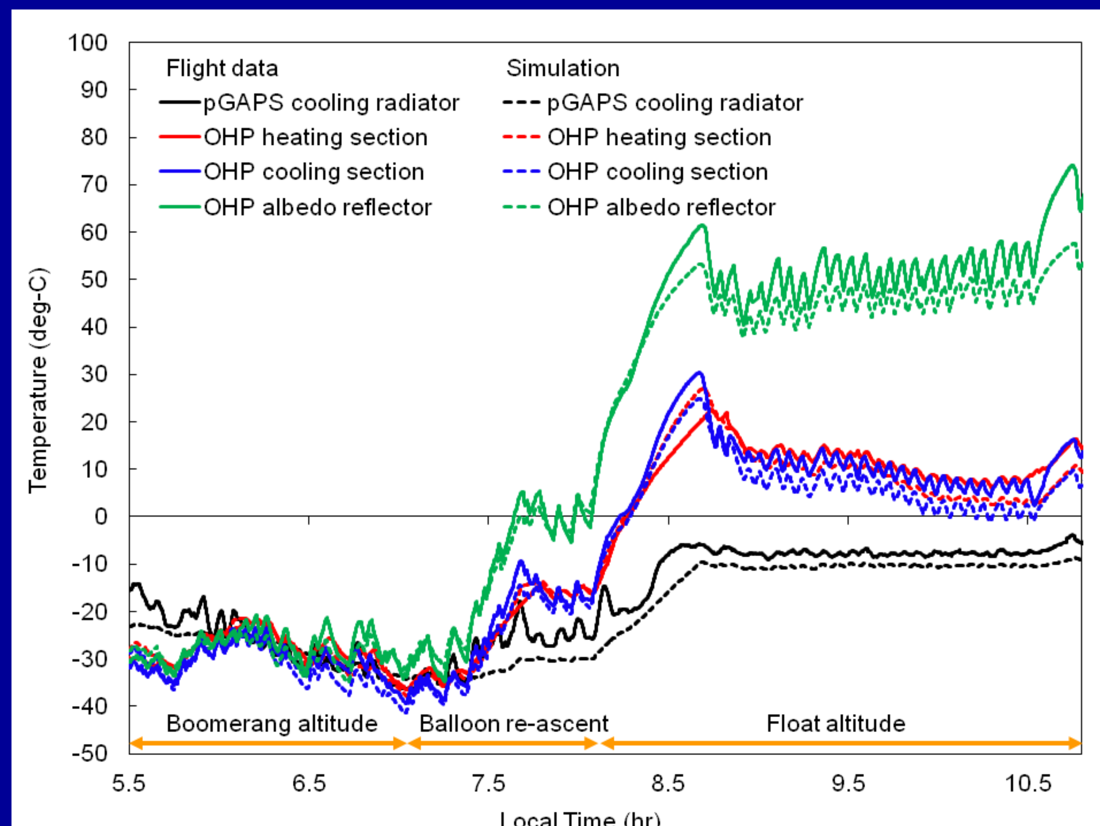




Flight Demonstration of OHP (2)

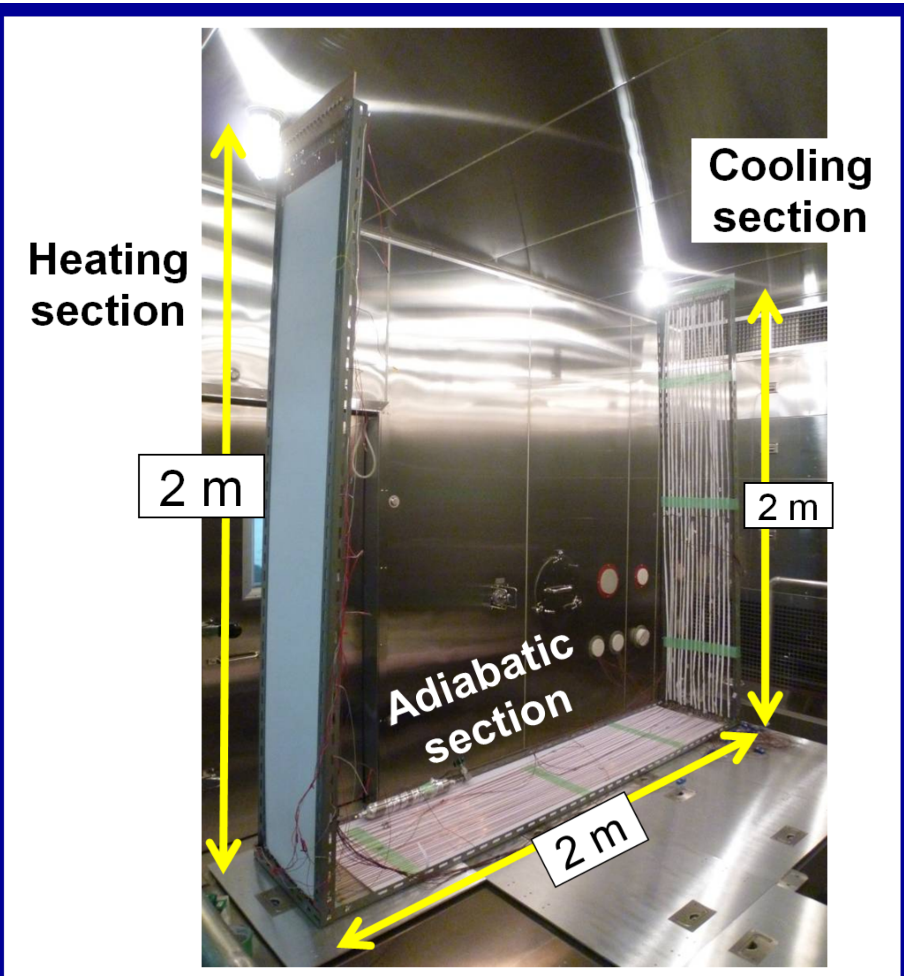
- Successful flight from TARF (Taiki, Hokkaido) on 3rd/June/2012.
- The OHP operated as expected throughout the 6-hour flight (conductance ~ 5 W/K).
- Transitional thermal calculation well reproduces the inflight temperature data.
- First successful OHP operation on a flying vehicle.
  (SDS-4 OHP was first successfully operated on 5th–8th/June/2012).

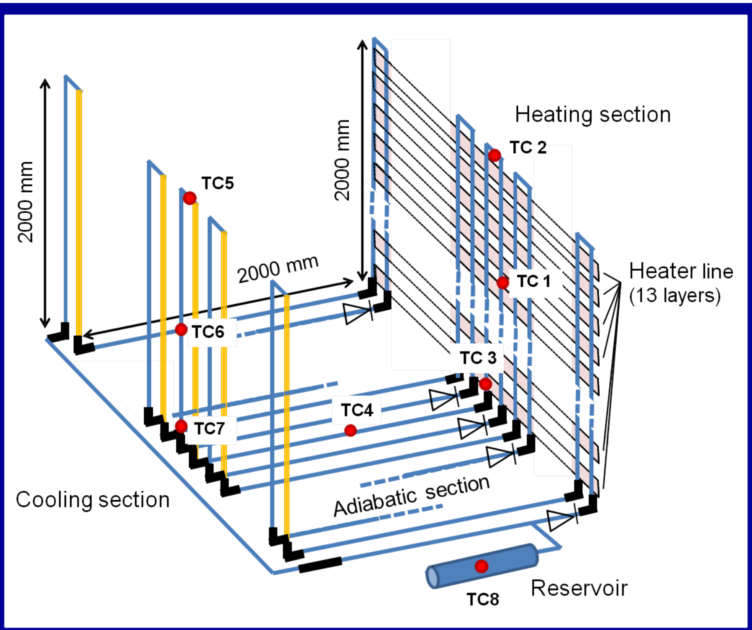




Meter-scale U-shaped OHP model

- Scaled-up OHP with actual meter scale (16 turns, turn length ~ 6m).
- It operates but meets the requirements partially especially at low temperatures.
  (The performance degradation at low temperature was more critical than the small U-shaped OHP).

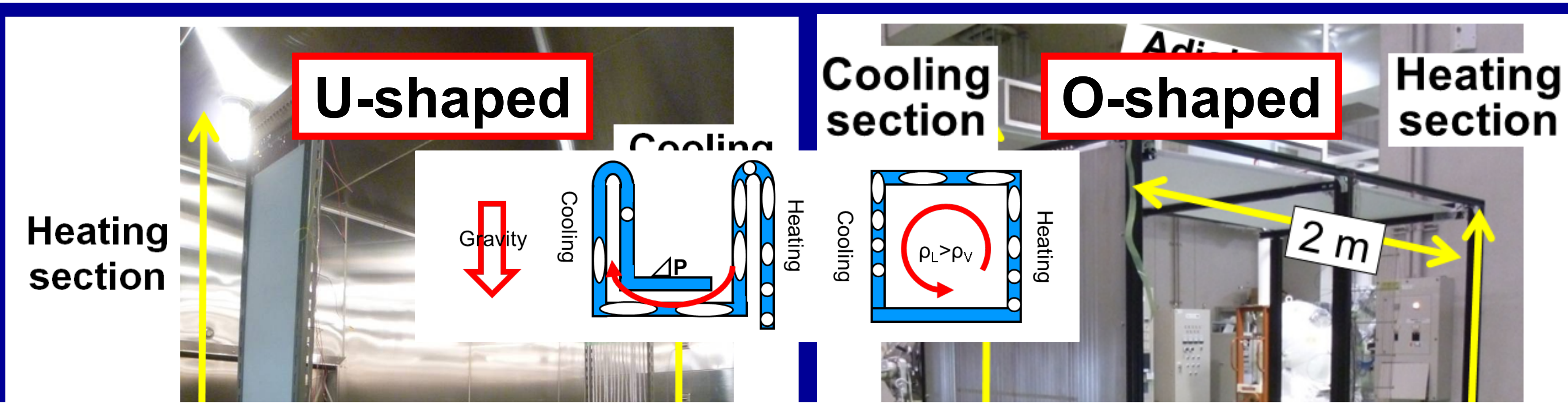


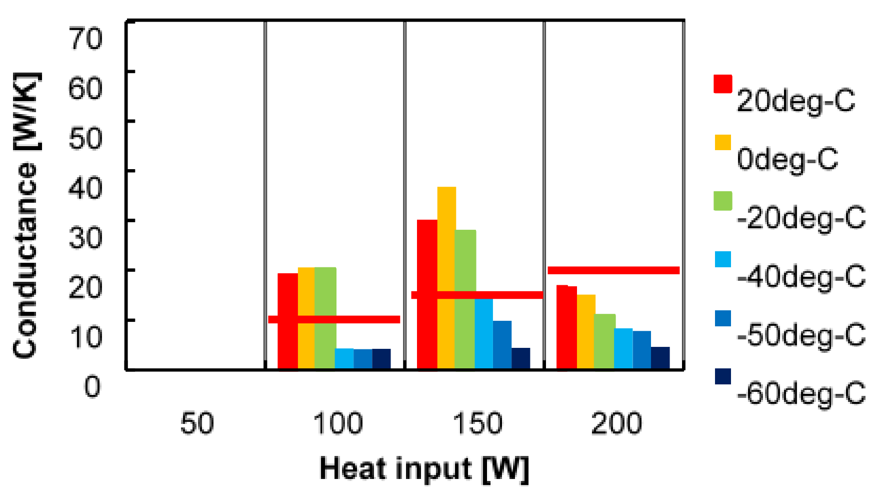


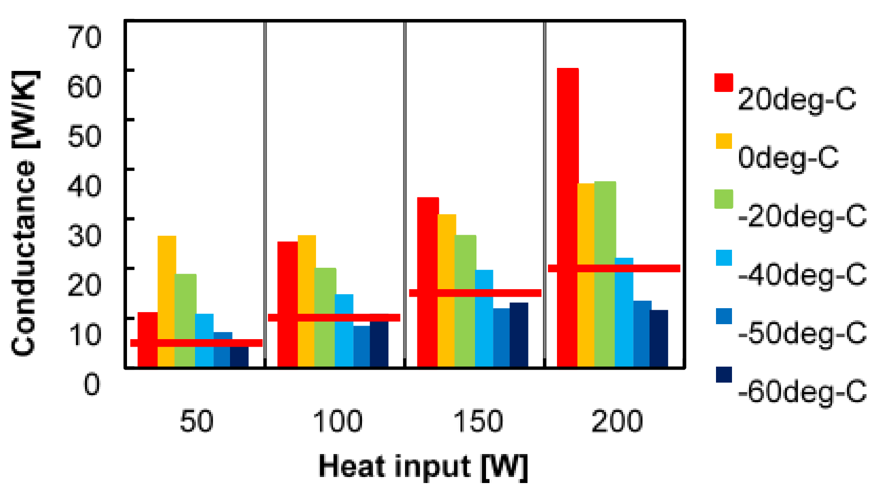
Working Fluid	R410A
Turn Length	6 m
Tube Diameter	1.0 / 1.6 mm
Number of Turn	16
Number of Check valve	8
Reservor Volume	300 ml

From U-shape to O-shape

- O-shape can expect larger gravity assist (body force) than U-shape “at the expense of ” additional tubes in the detector’s field of view.
- O-shape shows better performance than U-shape but still needs to be improved.

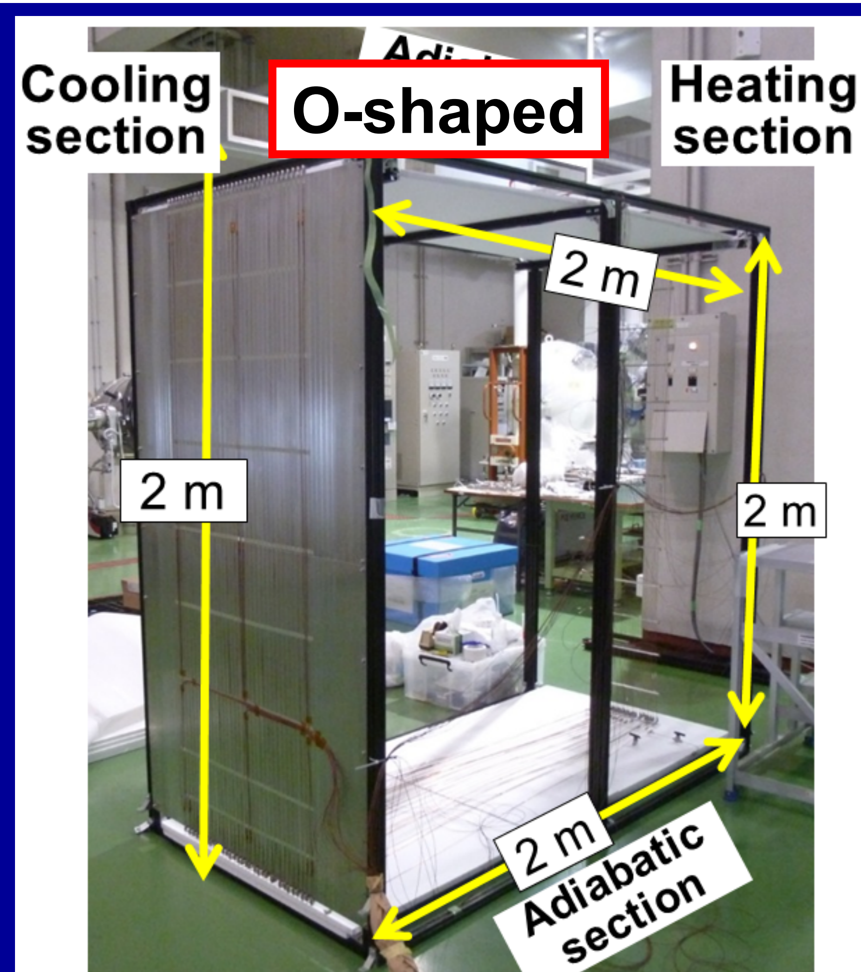


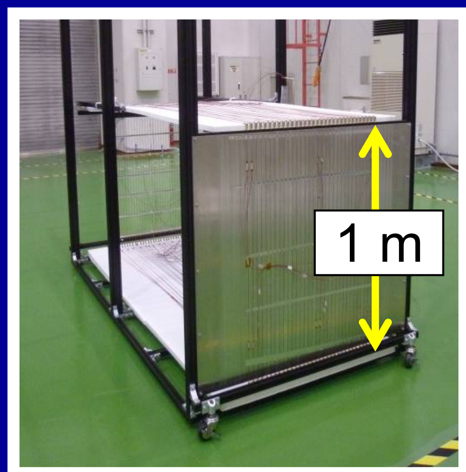




Detailed Studies of O-shaped OHP (1)

- Experimental study of gravity assist.
  - Decreasing the heating and cooling section height by half.
  - Inclining at various angles or toppling over sideways.

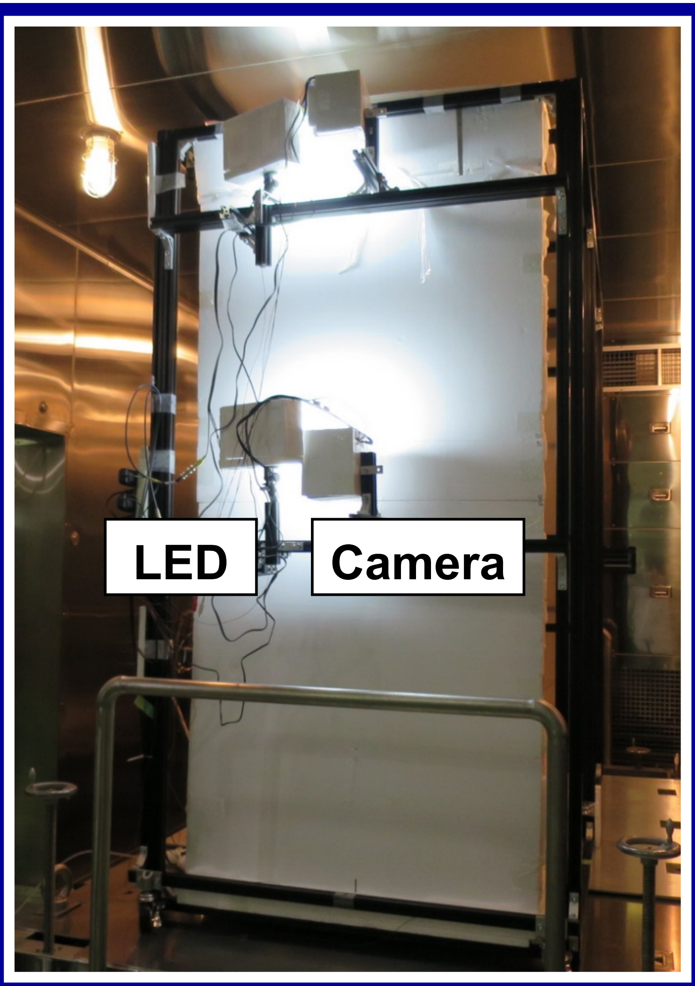


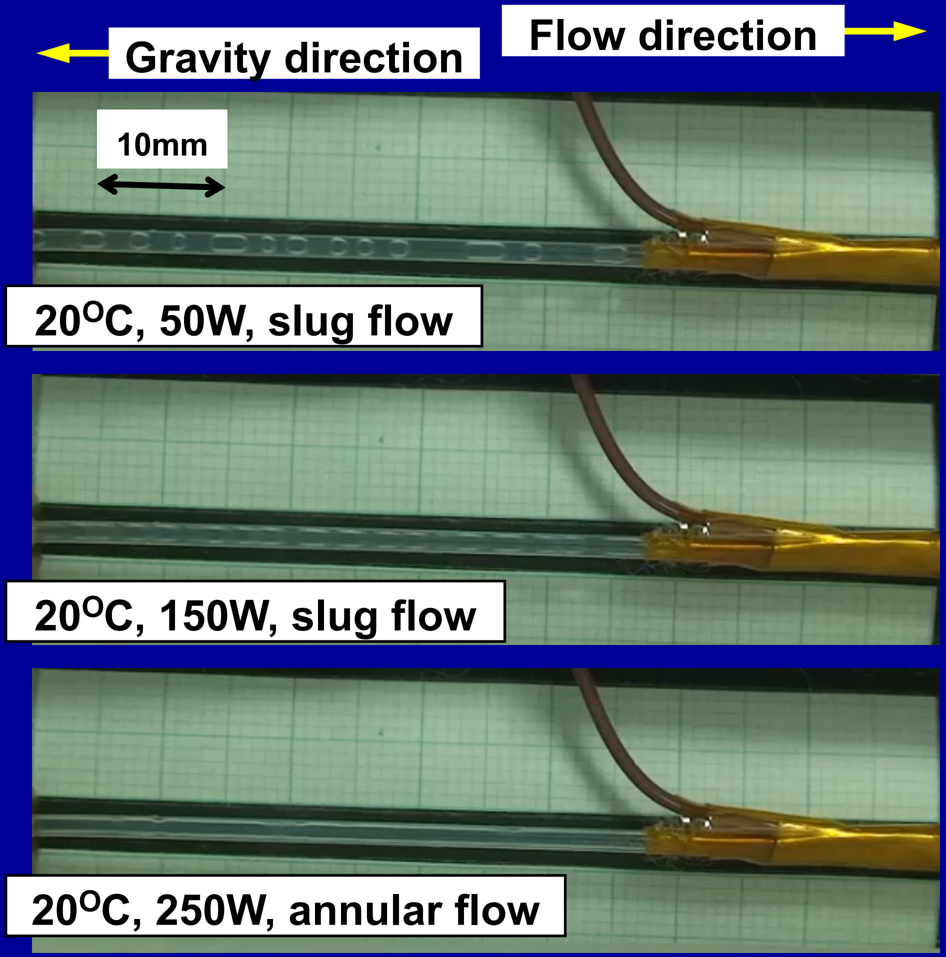


inclining

Detailed Studies of O-shaped OHP (2)

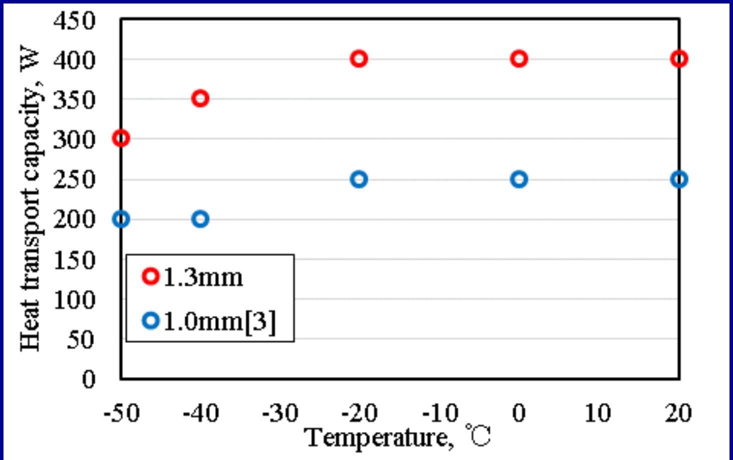
- Flow visualization to confirm:
  - Flow direction (one-way), flow speed, condensation length, flow regime.
- Monitoring of reservoir weight.

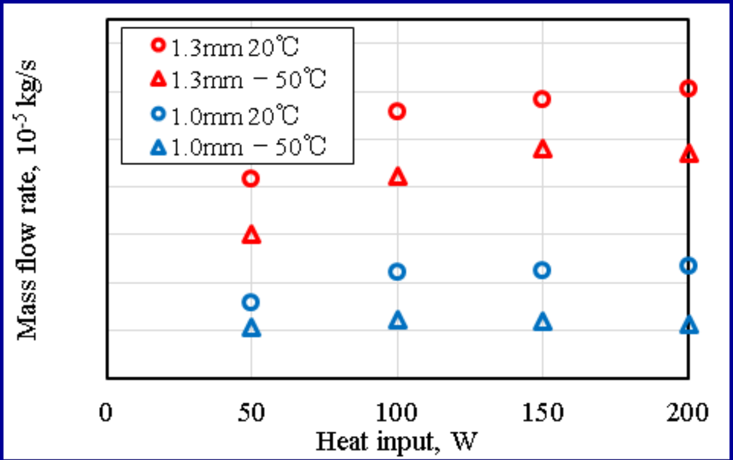


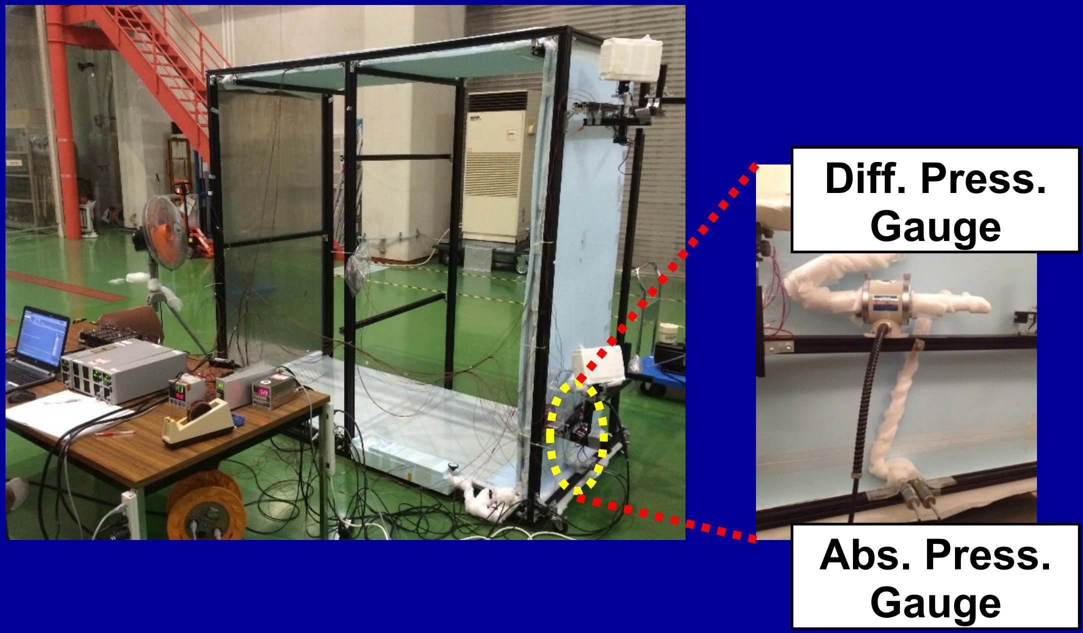


Detailed Studies of O-shaped OHP (3)

- Thickening the OHP-tube inner diameter (1.0mm → 1.3mm). ($Bo = \frac{g(\rho_l - \rho_v) D_{max}^2}{\sigma} \leq 4$)
  - Larger mass flow results in larger heat transport capability.
- Detailed measurements of pressure and temperature for deep understanding.

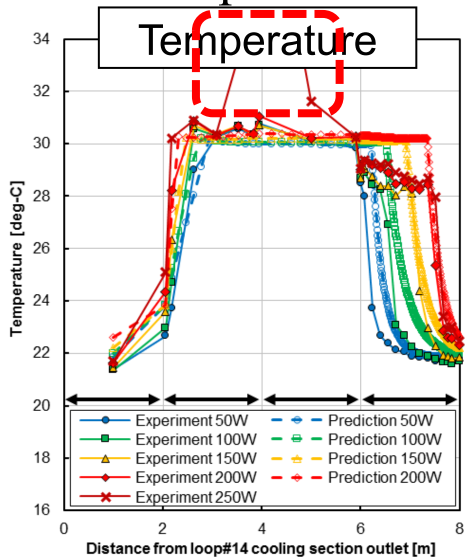


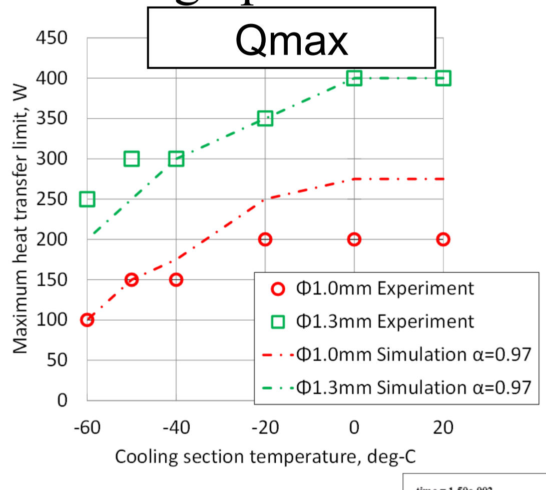


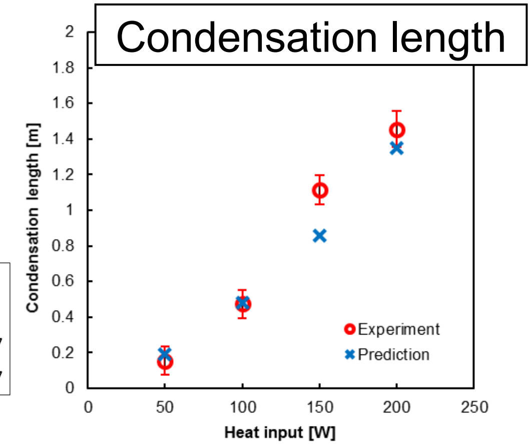


Numerical Simulations

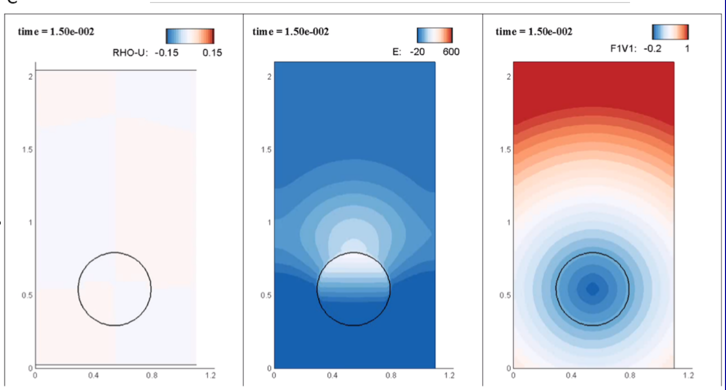
- One-dimensional "steady-state" simulation model.
  - (Drive force) = (Body force) ↔ (Pipe friction).
    No account of self-oscillation drive-force.
  - Consistent with meter-scale O-shaped OHP experimental results.
    Useful to optimize the OHP design parameters.





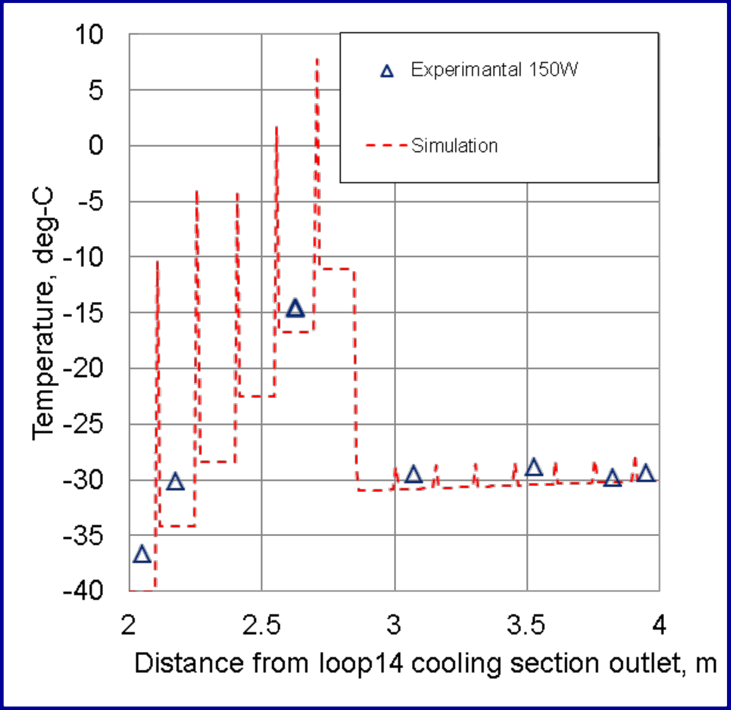


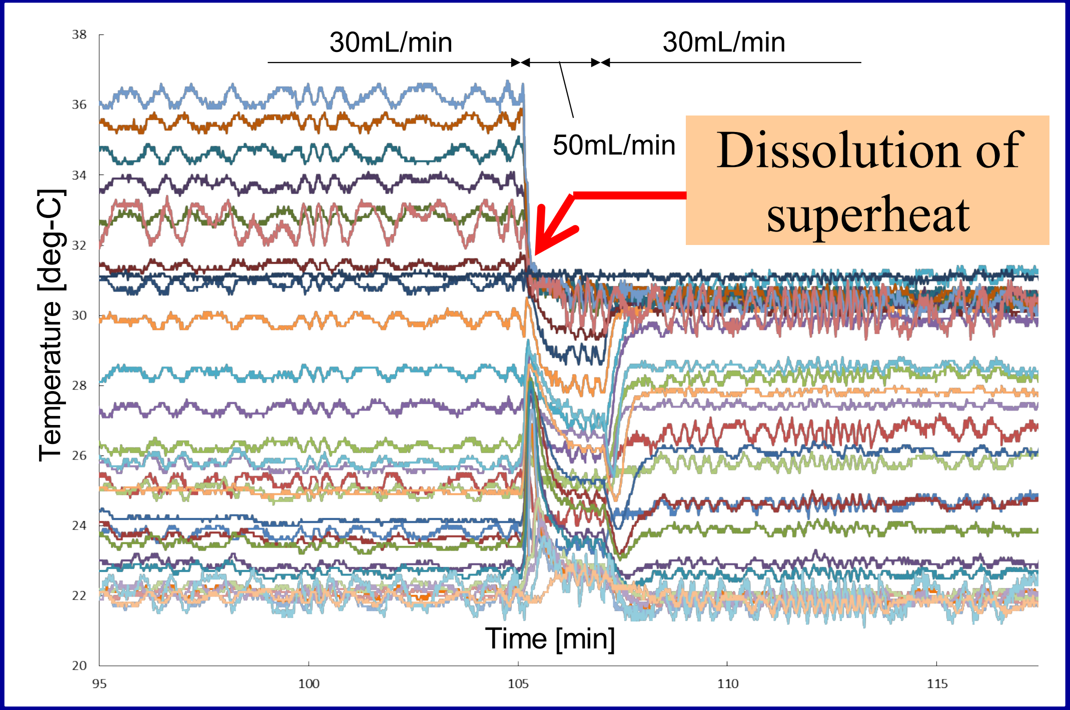
- Developments of non-equilibrium models.
  - An approach based on Faghri's 1-D model.
  - An approach to build 2-D/3-D models
    by using the ghost-fluid-method.



Dissolution of Superheat

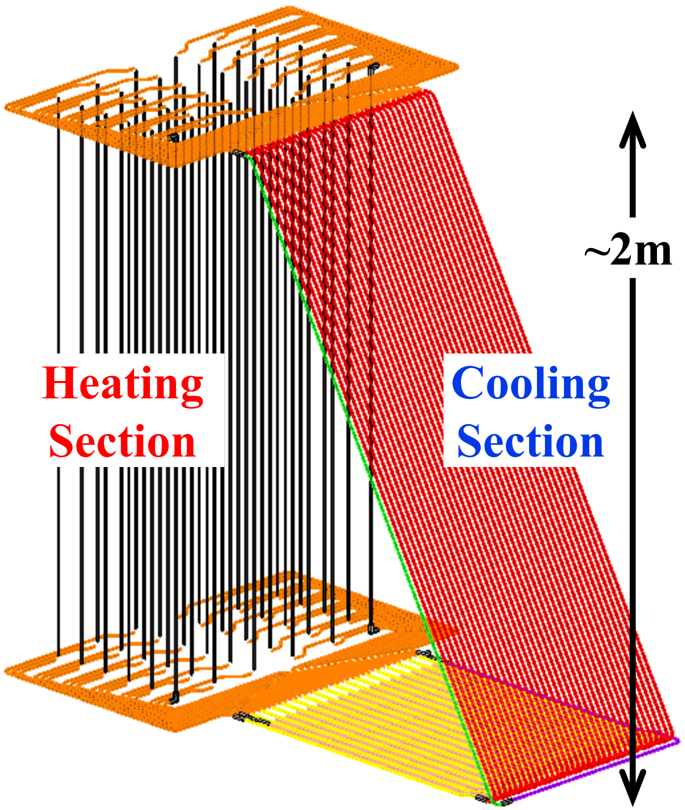
- Over-heat phenomenon was sometimes observed in the heating section. It can make the detector temperature inhomogeneous and can result in worse detector performance.
- We succeeded in simulating the superheat by implementing nucleate boiling physics.
- We also succeeded in solving the superheat problem experimentally by applying a short-time stimulus using either two-phase pump or auxiliary heater.
- This “active” solution extends the operational condition and makes the “passive” OHP more robust.





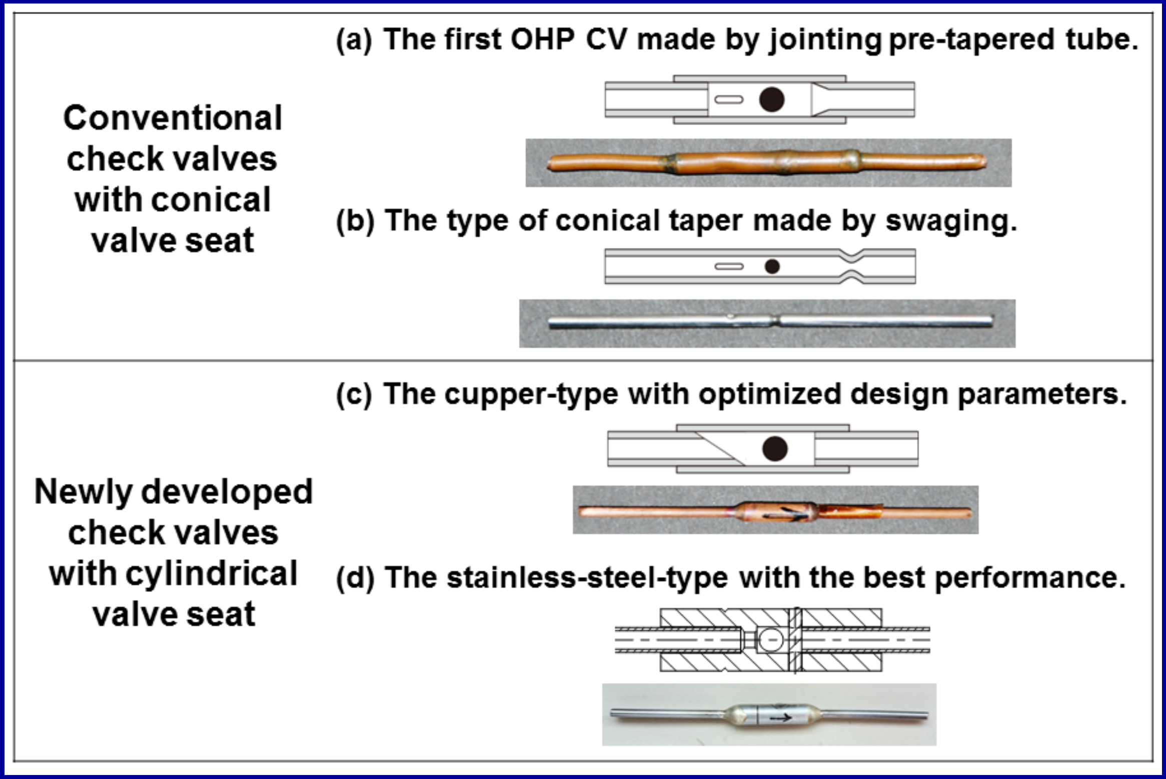
OHP model for practical studies

- Tests using an OHP model with more realistic complex configuration is in progress to make the system more reliable.



Improvement of Check Valve

- CV can make the OHP flow one-directional resulting in effective heat transfer.
- Requirements for "forward-flow coefficient", "backward sealing", "abrasion resistance", "technical feasibility of accurate fabrication", "reasonable price".
- By newly-developed cupper-CV, design parameters were optimized.
- Newly-developed stainless-steel-CV with cylindrical valve-seat meets all requirements and shows the best performance among all CV models.



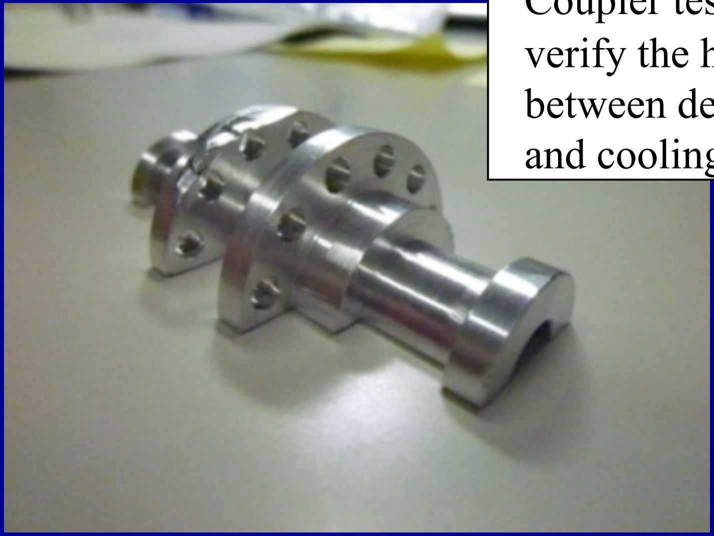
Summary

- An OHP cooling system has been developed for GAPS step by step.
- We succeeded in "wide-temperature-range operation", "3D routing", "flight demonstration", "scale-up of U&O-shape", "visualization", "numerical 1D equilibrium modeling", "improvement of CV", etc.
- By combining these many successful improvements, we are getting close to obtain an OHP design that fully satisfies the GAPS system requirements.
- Development of active control methods to dissolve superheat will increase the feasibility to realize the OHP system for GAPS.
- The basic system design must be fixed within around a year;
  The first GAPS flight in Antarctica is planned in around 2020.
- We expect our OHP technology can contribute to other experiments.

Appendix

Other Studies

- Thermal coupler.
- Local uniformity.
- Radiator.



Coupler test model to verify the heat coupling between detector holder and cooling pipe

Measurement of local temperature uniformity by using mockup detectors