Matching Technologies and Opportunities

MATEO

THE LOOP HEAT PIPE FOR AMS-02

Stefano Zinna
Marco Marengo

LSRM, Faculty of Engineering, University of Bergamo, viale Marconi 5, 24044 Dalmine, Italy

Inside ANTASME (I)

List of participants			
Number	Region	Name	Short name
1 (C)	LOM	Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano	DIA
2	LOM	Dipartimento di Elettronica e Informazione, Politecnico di Milano	DEI
3	LOM	University of Bergamo	UNIBG
4	LOM	Carlo Gavazzi Space SpA	CGS
5	LOM	A.D.S. International	ADS
6	NBR	University of Eindhoven	TUE
7	CAT	CENTRE INTERNACIONAL DE MÈTODES NUMÈRICS EN ENGINYERIA	CIMNE
8	CAT	COMPASS INGENIERÍA Y SISTEMAS	COMPASS
9	CAT	QUANTECH ATZ	QUANTECH

UNIBG is involved in the WP 8 and 9.

A collaboration with TUE is defined in order to obtain physical models from the FEM analysis for the lumped capacitance simulation of a propylene by-pass valve

2.3.1. Workpackage list				
WP number	Workpackage title	Start month	End month	Leading[1] participant n.
1	Project management	1	12	1
2	Automatic differentiation techniques	1	9	1
3	Innovative finite element methods for unsteady aeroelastic analysis	1	12	7
4	Advanced evolutionary algorithms for transonic drag reduction and high lift of 3D configuration using unstructured FEM	1	12	7
5	Simulation of massively controlled space tele-scopes	1	12	1
6	Object-oriented modelling of mechatronic elec-trohydraulic systems	1	12	2
7	Object-oriented modelling of spacecraft dynamics	1	12	2
8	SINDA/FLUINT simulation of the LHP prototype	1	12	3
9	Lumped and "distributed" analysis of the by-pass valve	3	11	3
10	Dissemination of results	1	12	1

8.1	8	Simulation of the LHP in orbital conditions	4	PU
8.2	8	Simulation of the LHP prototype in the thermal chamber (ground test)	10	PU
8.3	8	Comparison of numerical data and ground test results	12	PU
8.4	8	Definition of data input and output struc-tures for future implementation in general multidisciplinary codes	12	PU
9.1	9	Analytical model of the by-pass valve	6	PU
9.2	9	FEM analysis of the by-pass valve	9	PU
9.3	9	Implementation of the FEM data in the SINDA/FLUINT network scheme	11	PU

The construction of the thermal chamber in China is delayed and at the present conditions is likely that the comparison of the ground model simulation with experiments (i.e. the WP 8.3) will not be carried out

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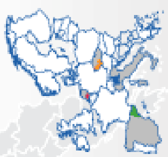


Inside ANTASME (II)

2.3.4. Workpackage description

Workpackage n.	8	Start month		1	End month				12	
Workpackage title[1]	SINDA/FLUINT simulation of the LHP prototype									
Participant number	1	2	3	4	5	6	7	8	9	TOT
Person-months			12	1		1				

Objectives

A comparison between the microgravity and the unit gravity model is important to understand as much as possible of the LHP working. It is desirable to understand the behaviour under both conditions because, although a satellite's operational life is spent in orbit under microgravity conditions, the satellite undergoes extensive ground testing (1 g) before launch to ensure all components are working correctly. Therefore the objectives of this WP are:
1) building the network scheme of the propylene loop heat pipe
2) simulating the LHP orbit and ground behaviour using Carlo Gavazzi Space data for the orbits
3) modelling the physical processes in the LHP evaporator and condensator using the last results in the literature
4) implementing the results obtained in the WP 9 using a "mixed approach"

Description of work

Using a lumped code (SINDA/FLUINT) every component of the AMS propylene Loop heat pipe will be modelled. The boundary conditions will be time varying elements, simulating different orbital periods defined through previous flight conditions supplied by the Carlo Gavazzi Space. The same model will be then adapt to simulate a ground LHP, looking at empirical correlation in gravity for the two-phase thermodynamics and flow. Also the LHP boundary conditions will be varied in order to assure that the same heat transfer dissipated during flight conditions will be reached when also natural convection is present, i.e. in the thermal chamber. The 1g model will be compared with results obtained in the thermal chamber experiments in China typically by correcting the unknown conductances in the model. The whole LHP will be then reduced to an "object" in which input data are represented by the boundary conditions both for the evaporator and the radiator and the results are constituted by the thermodynamics values of the propylene in the points necessary to fix the loop working and failure. Finally the results of the WP x.2 will be used in a sub-network set regarding the by-pass valve regimes, using an innovative "mixed approach" from "distributed" simulation to the lumped simulation code.

Expected results

The comparison between the microgravity and the gravity models will give us the necessary information about the optimal ground testing, which will be applicable for the LHP final operational testing. The experimental data will help to tune the behaviour in the evaporator and in the condenser where the two-phase heat transfer is difficult to predict. The definition of data input and output structures reduce the LHP model to few objects necessary in a future implementation in multidisciplinary codes. The usage of the FEM results describing the by-pass valve inside the SINDA/FLUINT code will help to understand the best implementation strategies in such "mixed approach".

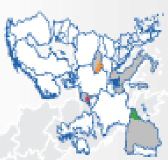
Deliverables

8.1 Simulation of the LHP in orbital conditions
8.2 Simulation of the LHP prototype in the thermal chamber (ground test)
8.3 Comparison of numerical data and ground test results
8.4 Definition of data input and output structures for future implementation in general multidisciplinary codes

OBTAINED RESULTS

A Loop Heat Pipe model was built with the following mesh characteristics:
The pipe is divided in **93 thermal nodes**: 15 in the vapour line (1 temperature-varying capacitances), 13 in the liquid line (1) and 65 in the condenser line (1). The radiator is divided in 176 thermal nodes having temperature-varying capacitances. The evaporator is constituted by 5 capacitance nodes. The fluid line has **93 fluid nodes**. The evaporator 3 fluid nodes (reservoir, wick & grooves).
The physical model included: **SINGLE-PHASE** and **TWO-PHASE** regimes.

The heat transfer coefficient in microgravity is 50% less than the correspondent in normal gravity when the flow pattern is bubbly or slug. In that case a parameter that cut 50% heat transfer coefficient's value can be imposed.
The orbital simulations were then obtained for the worst conditions: a) Hottest boundary conditions and maximum power to reject; b) Coldest boundary conditions and minimum power



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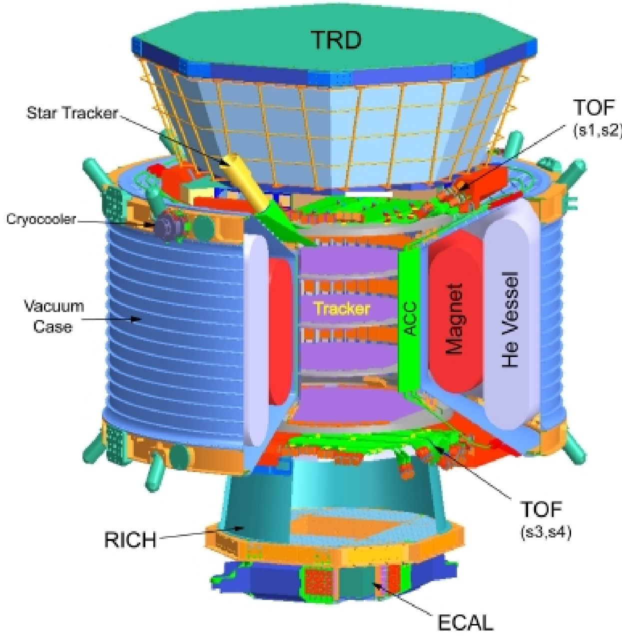
AMS-PROJECT

- The Alpha Magnetic Spectrometer is a space born detector for cosmic rays built by an international collaboration. AMS will operate aboard the truss of the International Space Station (ISS) for at least 3 years (2008?)

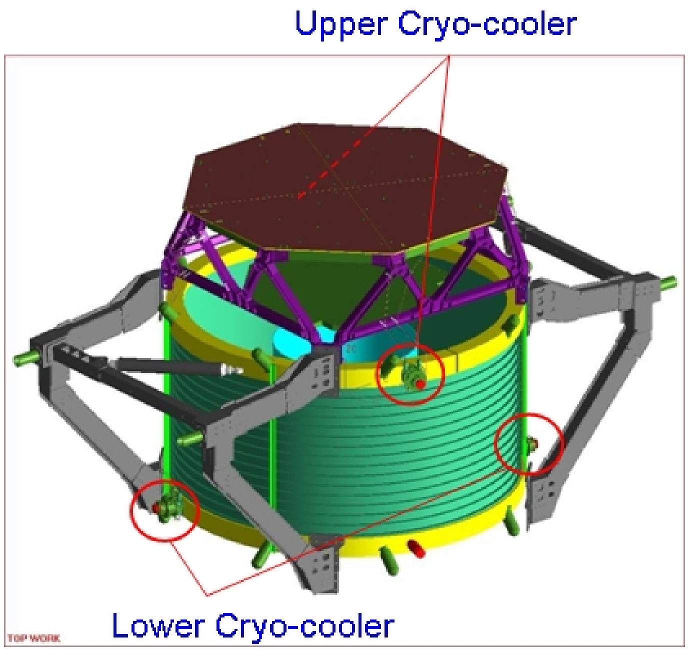


- The central tracker is the core of AMS-02, both conceptually and geometrically. It measures trajectories of particles in a magnetic field provided by the superconducting magnet.

AMS-THERMAL CONTROL

- Since the magnet is a lot colder than the ambient environment of the Space Station, it has to be cooled actively. The principal coolant is a volume of superfluid helium in a tank kept in indirect thermal contact with the magnet
- The heat is transferred into the main helium tank, where it is consumed by boiling superfluid helium. Ultimately, heat is removed from there by venting this induced helium vapor into space

- Since the amount of helium is limited, this can become the limiting factor that finally determines the end of the experiment at large. To avoid that as long as possible AMS-02 is equipped with 4 cryo coolers — heat pumps based on the principle of the Stirling cycle of classical thermodynamics.



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CRYO-COOLER

- Conceptually, cryo-cooler remove heat energy at what is called their “cold tip”, and transfer it forcibly to a warmer body thermally connected to their other end: the “sink”.

- The pumps are operated under some conditions about their temperature

Minimum (+heat lift)	60+3 W / cryo-cooler
Maximum (+heat lift)	150+8 W / cryo-cooler
Nominal (+heat lift)	100+5 W / cryo-cooler

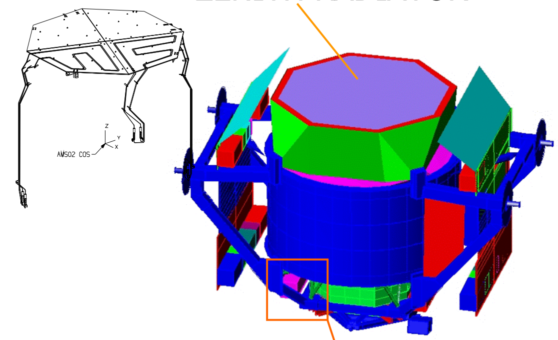
Min. turn-on and operational temperature of the Cryo-cooler	-10°C
Max. operational temperature of the Cryo-cooler	+40°C
Min. non-operational and survival temperature of the Cryo-cooler	-40°C
Max. non-operational and survival temperature	+40°C

Matching Technologies and Opportunities

AMS-LHP

- Loop Heat Pipes (LHP) are robust, self-starting, passive two-phase thermal transfer devices. Therefore the LHP is the link between the Cryo-cooler and the radiator.
- The power is dissipated by the radiative heat transfer towards external environment (zenith radiator)

ZENITH RADIATOR



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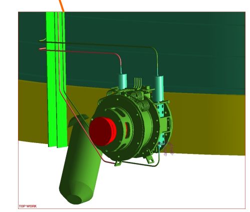
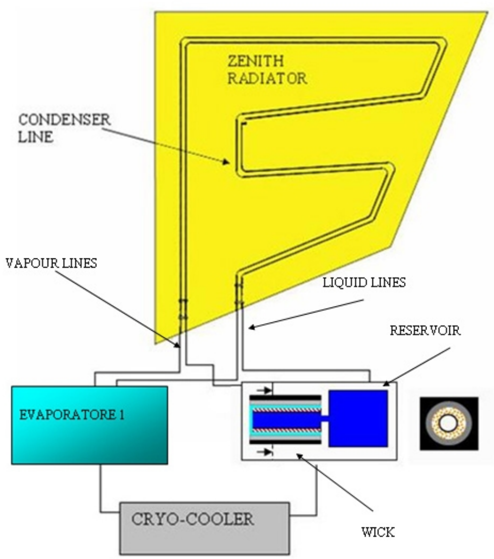
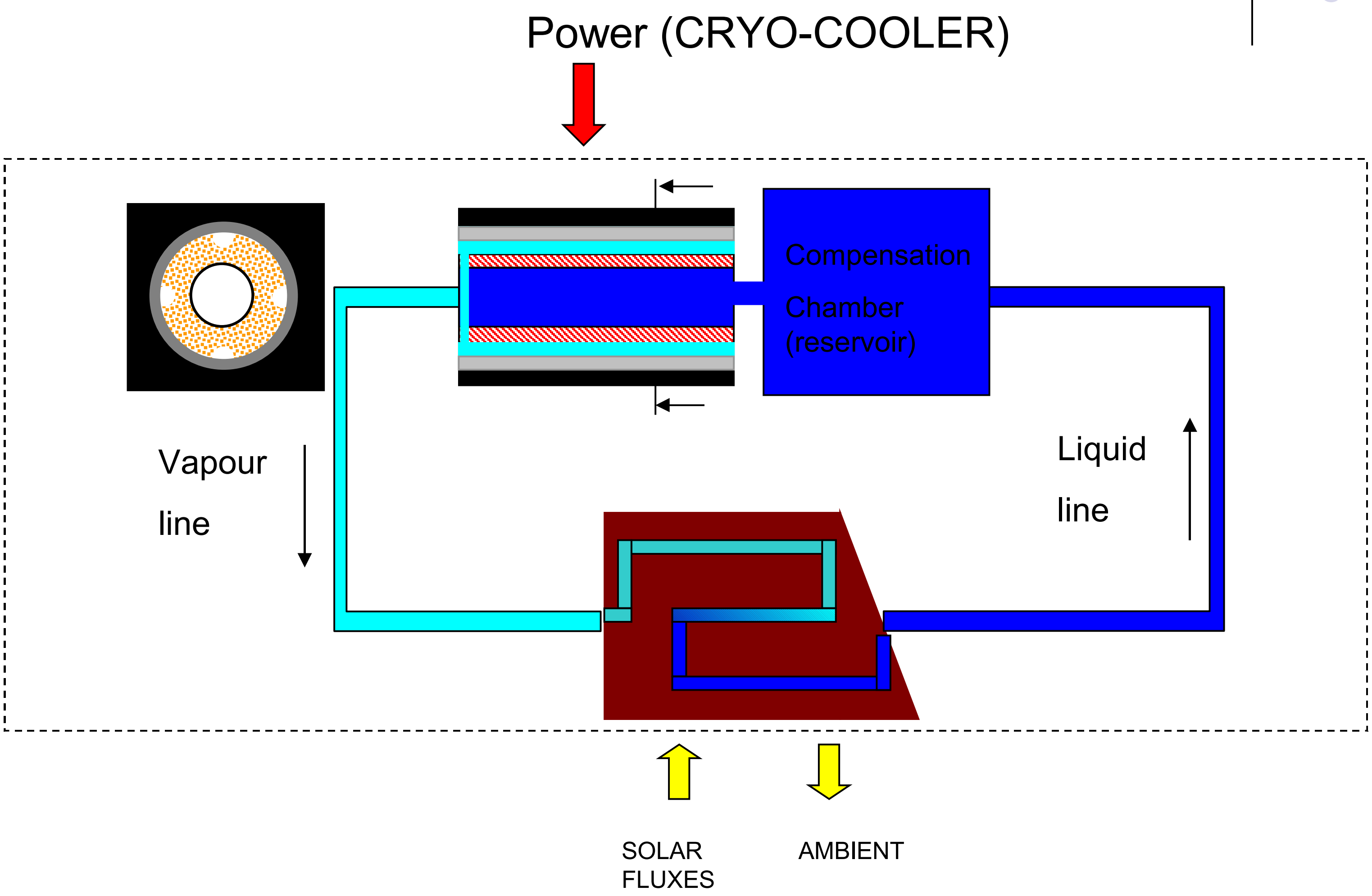
CRYO-COOLER





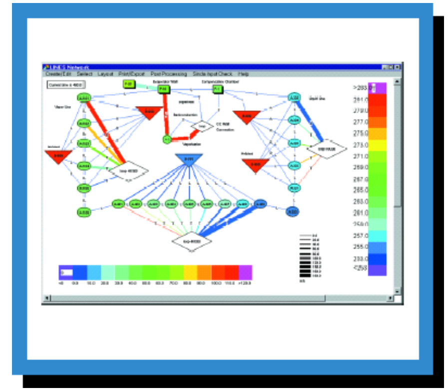
- Every cryo-cooler is connected to two LHPs (redundant). Working mode: 2-LHP model (nominal way) 1-LHP model (failure way)
- Every LHP transfers the power towards a quarter of the zenith radiator

LHP-COMPONENTS

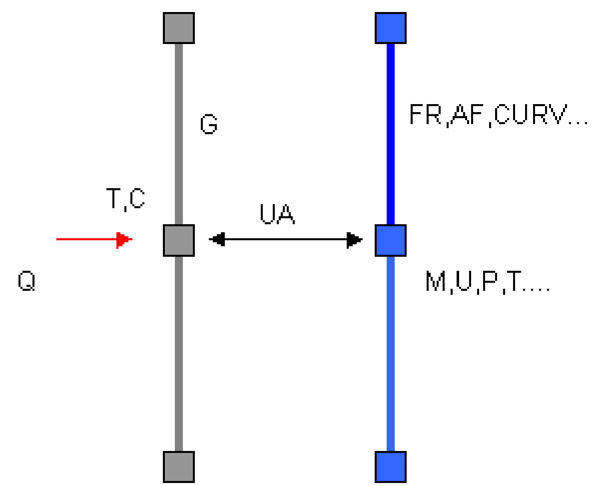


SINDA/FLUINT

- Using a numerical code (SINDA/FLUINT) developed by NASA, a global loop model can be designed. SINDA is a network-style (resistor-capacitor circuit analogy) thermal simulator.



- SINDA: The user poses a heat transfer problem by creating an arbitrary network of temperature points (*nodes*) connected by heat flow paths (*conductors*). FLUINT: The user poses a problem by creating an arbitrary network of thermodynamic points (*lumps*) connected by fluid flow passages (*paths*).
- The user may also define heat transfer routes (*ties*) between SINDA nodes and FLUINT lumps to simulate convection.



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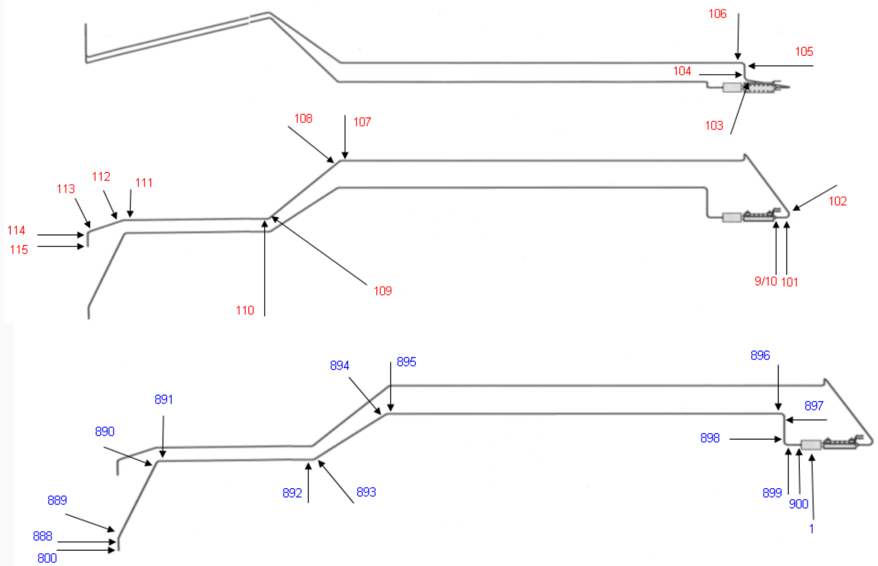
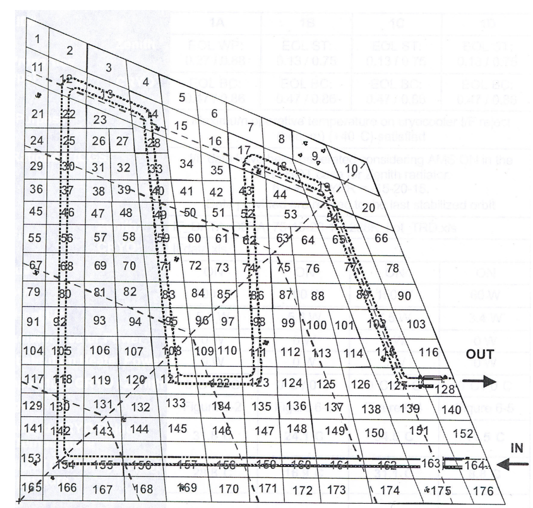
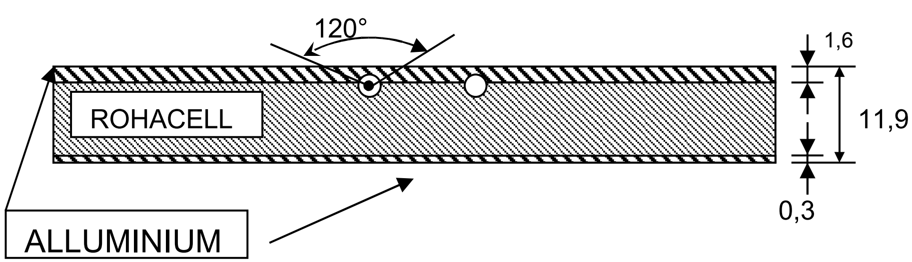
LHP- NUMERICAL MODELITATION



- The pipe is divided in **93 thermal nodes**: 15 in the vapour line (1 temperature-varying capacitances), 13 in the liquid line (1) and 65 in the condenser line (1). The radiator is divided in 176 thermal nodes having temperature-varying capacitances. The evaporator is constituted by 5 capacitance nodes.
- The fluid line has **93 fluid nodes**. The evaporator 3 fluid nodes (reservoir, wick & grooves)



- The radiator is divided in **176 thermal nodes** having temperature-varying capacitances; The condenser nodes are connected to the radiator one through a radial conductance



SINGLE PHASE FLOW

FRICTIONAL PRESSURE DROP CORRELATION

- Single-phase pressure drops are calculated using a Darcy friction factor. This factor (as represented on a Moody chart) is a function of Reynolds number (*Re*) for laminar flow, and a function of both Reynolds number and wall roughness ratio (roughness over diameter, e/D) for turbulent flow.
- A function from Churchill is used to analytically represent the Moody chart:

$$f = 8 * \left(\left(\frac{8}{Re} \right)^{12} + \frac{1}{(A+B)^{3/2}} \right)^{1/12}$$

- Curved passages result in secondary flows that increase pressure drop. The radius of curvature (the default is 1.0E30 meaning a straight duct) is supplied so that laminar and turbulent friction factors are applied, as well as correlations for critical Reynolds number

HEAT TRANSFER COEFFICIENT

- The heat transfer coefficient for laminar flow is:
- For turbulent flow the common Dittus-Boelter correlation is used:
-
- Hausen's transition correlation is used for Reynolds numbers between approximately 2000 and 6400:

TWO PHASE FLOW FRICTIONAL PRESSURE DROP

- In bubbly and slug flow regime predicted pressure drops are based on the McAdam's formulation for homogeneous flow: the basic assumption of this model is that the two phases are well mixed and the velocities of the two phases are equal. The mixture density is given by:

$$\frac{1}{\rho_m} = \frac{x}{\rho_G} + \frac{1-x}{\rho_L}$$

- The mixture viscosity can be the liquid viscosity or one among the several mixture correlations (Dukler et al. (1964))
- The friction factor can be calculated from Blasius equation:

$$\left(\frac{dp}{dz}\right)_F = \frac{2}{D} C_f \rho_m U_m^2 \qquad \mathrm{Re} = (\rho_m U_m D)/\mu$$

- When the regime is determined to be annular, the Lockhart-Martinelli correlation is used where the pressure drop are connected to Martinelli parameter :

$$X^2 = (dp/dz)_L / (dp/dz)_G$$

- Both McAdam (homogeneous model), and Lockhart-Martinell (as Friedel model too) give good predictions for pressure drop in microgravity. **(Zhao L. Rezkallah K.S., 1995. Pressure drop in gas-liquid flow at microgravity conditions. *Int. J. Multiphase Flow* 21, 837-849)**

TWO PHASE FLOW HEAT TRANSFER COEFFICIENT

BOILING

- The basis of the nucleate boiling correlation is Rohsenow's correlation for pool boiling:

$$U = \mu_l \left(\frac{\Delta T}{h_{fg}}\right)^2 \left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{1/2} \left[\frac{C_{p,l}}{\mathrm{Pr}_l^S \cdot C_{sf}}\right]^3$$

- The high quality film boiling correlation is simply the single phase Dittus-Boelter correlation for vapour using the current vapour mass fraction and void fraction.
- The heat transfer coefficient in microgravity is 50% less than the correspondent in normal gravity when the flow pattern is bubbly or slug. In that case a parameter that cut 50% heat transfer coefficient's value can be imposed. (**Rite R. W., Rezkallah K. S. , 1997. Local and mean heat transfer coefficients in bubbly and slug flows under microgravity conditions, *International Journal of Multiphase Flow* 23, 37-54**).

CONDENSATION

- The condensation heat transfer coefficient for two-phase flow is based on Shah's correlation (**Lu Qing, Suryanarayana N. V., 1993. Film condensation in a horizontal rectangular duct**)

$$Nu = Nu_{lo}\left[(1-x)^{0,8} + \frac{3,8x^{0,76}(1-x)^{0,04}}{p_r^{0,38}}\right]$$

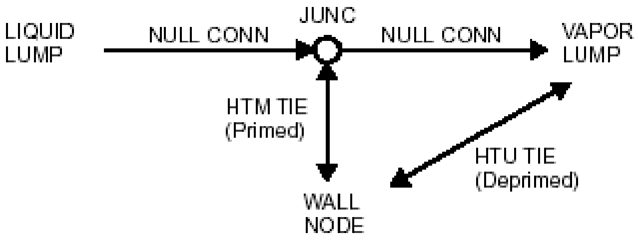
- where:

$$p_r = P / P_C$$

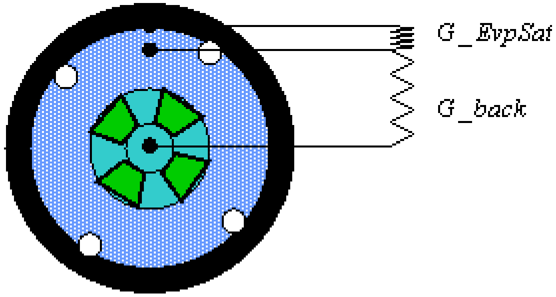
$$Nu_{lo} = 0,023\mathrm{Re}_{lo}^{0,8} \cdot \mathrm{Pr}_l^{0,4}$$

Wick- PHYSICAL MODELITATION

The capillary device is working or not working (said **primed** or **deprimed**):1) the pressure differential exceeds the capillary limit, 2)the liquid pressure is greater than that of the vapor, 3)too much liquid appears in the "vapor" end, 4)an excessive pressure drop from the liquid lump to the capillary interface.

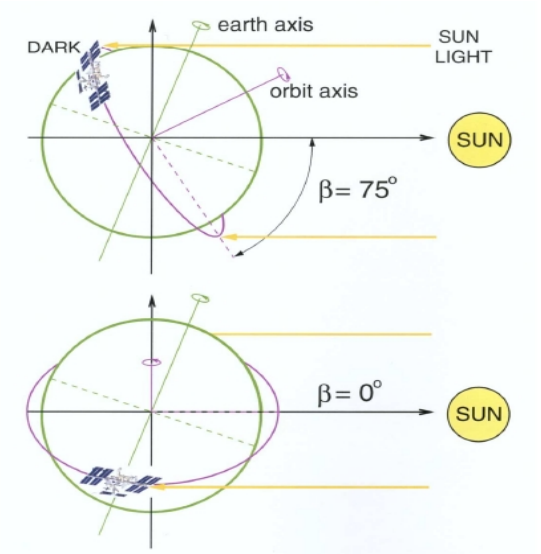


- Due to the requirement of very fine pore size, the primary wick in the LHP is sintered metal powder wick (wet sintered nickel: **Heat Pipes, Dunn and Reay**)
- Secondary wick is made of stainless steel mesh with the cell dimension of 40 mm.
- The steady state operating temperature is an important parameter to fix the working of the LHP so the value 13.4 is set as ratio between the two conductances in the wick (**Heat and Mass Transfer in Loop Heat Pipes, T. Hoang , J. Ku, ASME Heat Transfer Conference July 2003**)

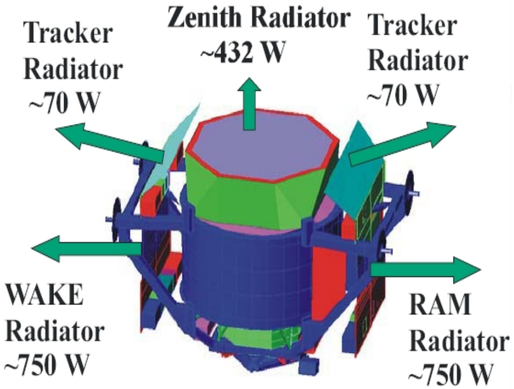


BOUNDARY CONDITIONS

- The primary external factor in the thermal environment is solar illumination. This depends primarily on the angle between the ISS orbital plane and the direction to the Sun (beat angle). For the ISS orbital inclination (51.6°) and the tilt of the Earth's axis (23.5°), the beta angle varies between -75.1° and +75.1°, modulated by the seasons.



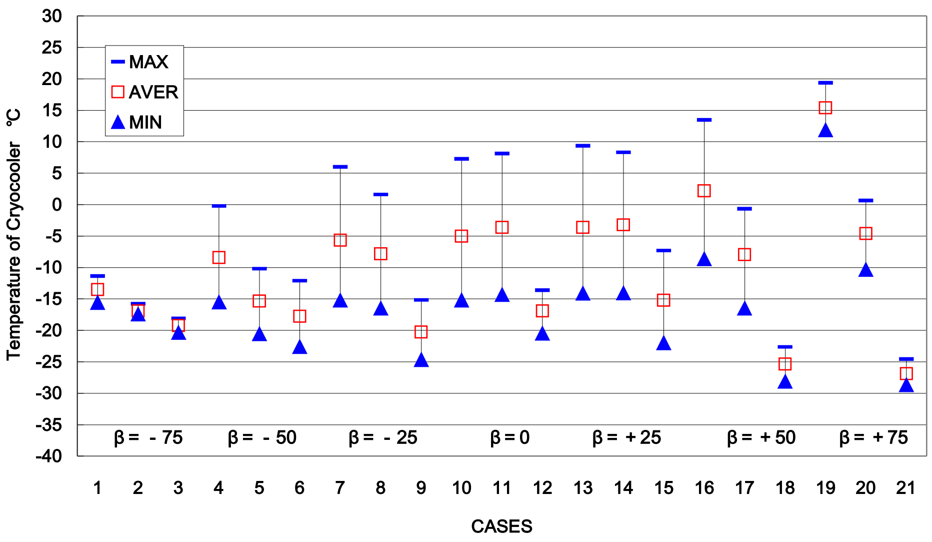
- Different parts of AMS are exposed to different amount of direct sunlight at different times, depending on the ISS attitude, which is expressed in the aeronautical coordinates of yaw, pitch and roll (Y/P/R).
- Different radiators are used to dissipate the overall power.



21 CASES

- Considering the influence of external loads as well as the ISS and internal loads on AMS-02(cryocoolers), the orbit environment, varying with Beta angle and ISS attitude, a system level model is established. Finally, for the LHP system, 21 cases are selected as a subset of the full factorial scan of 7 possible beta angles (from -75○ to +75○ with the interval equal to 25○) and each one of the three Euler Angles (Yaw, Pitch and Roll) considered at their maximum value, their minimum and an average one, corresponding to the Minimum Propulsion Attitude (MPA).

- For each Beta angle we have selected the hottest and the coldest attitude, as well as the MPA one, thus coming to the 21 cases mentioned before.



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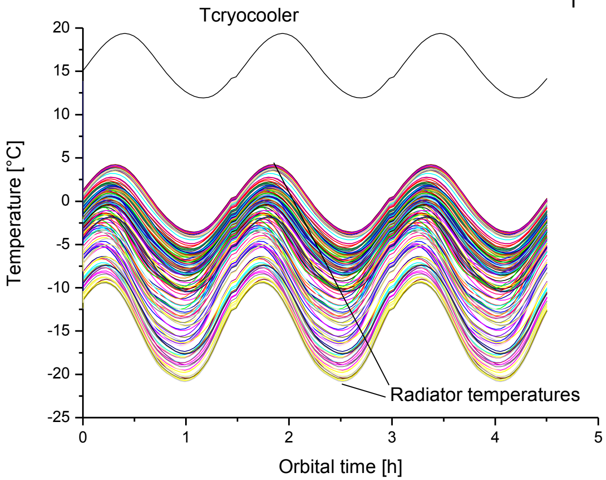
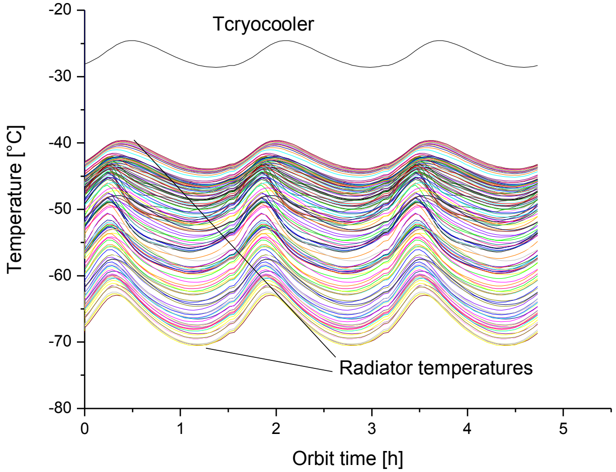
NOMINAL CASES

- The hottest case occurring on attitude of Beta angle =+75○, Y/P/R =-15/-20/-15; It is orbits without eclipse, for which a suitable roll angle provides a constant pointing to the sun of the zenith radiator; the temperature of cryocooler is fluctuating from 11.9°Cto 19.3°C due to the variation of orbit environment but still within the required range, and temperatures of radiator are in the range of [-20.8°C, +4.2°C].

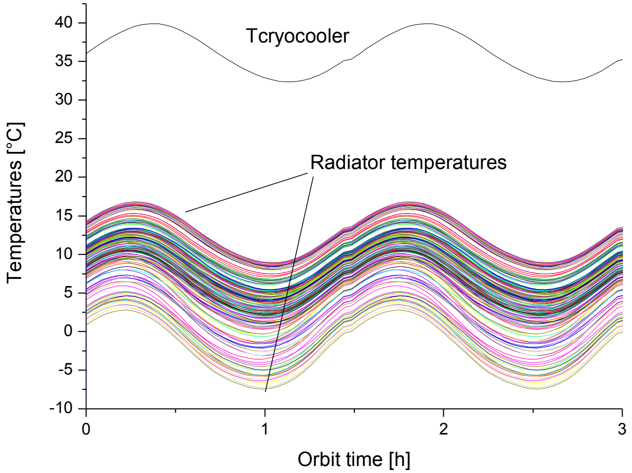


- The coldest case on attitude of Beta angle = +75○, Y/P/R= -15/+15/+15; it is orbits without eclipse, for which a suitable roll angle provides a continuous pointing to the deep space; Under this environment, the cryocooler temperature would be below its minimum operational temperature -10°C and reaching almost -30°C for some orbit time.

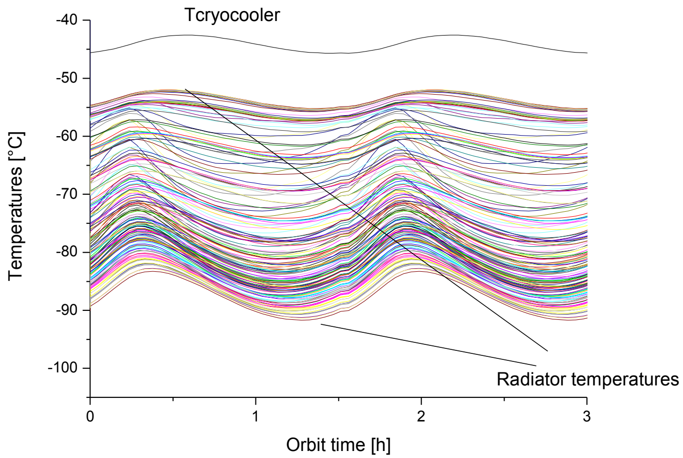


WORST CASES

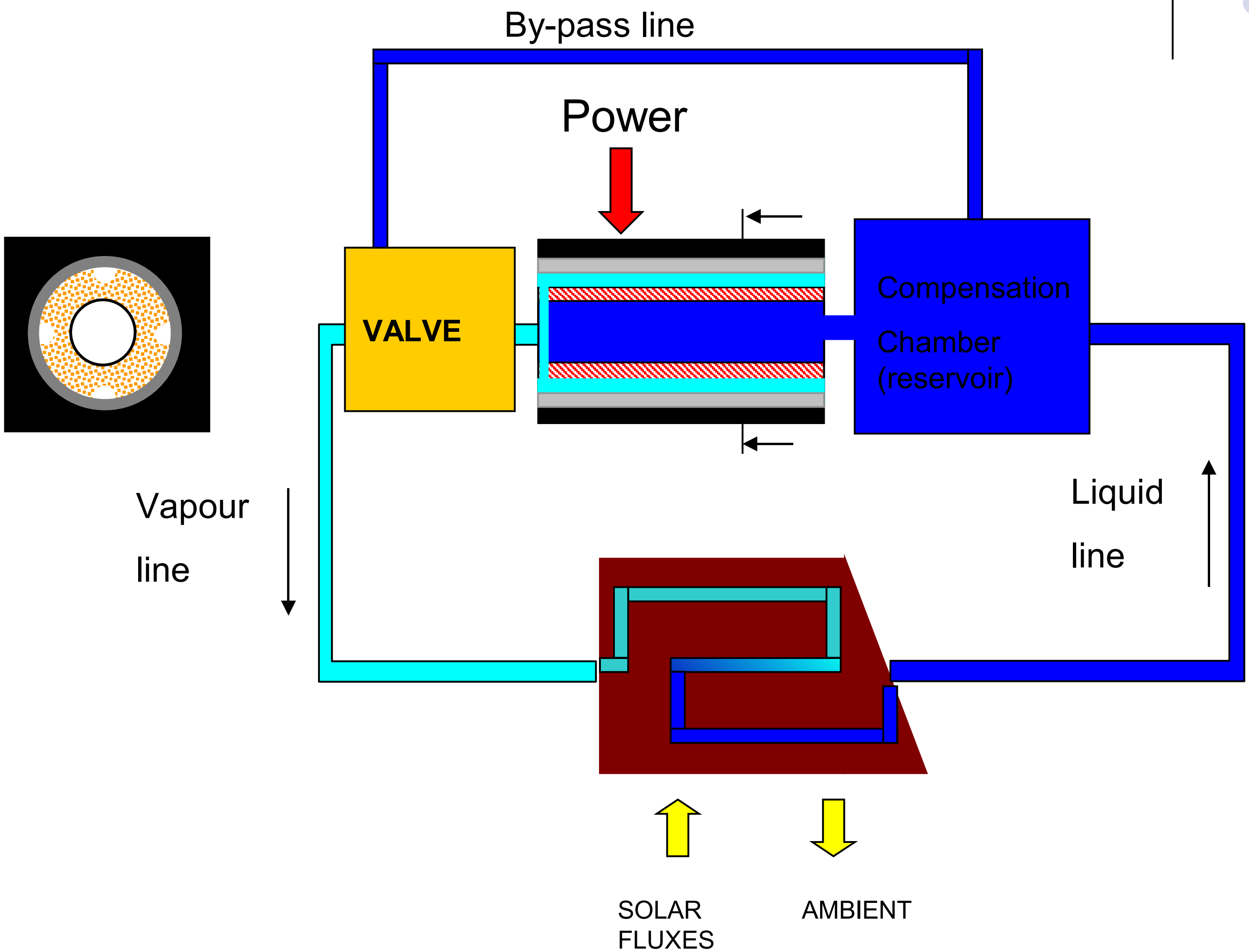
- Hottest environment and maximum dissipation 158W the proposed propylene LHP system can transfer 158W from cryocooler under the hottest environment, and get the maximum temperature of cryocooler of +39.9℃;



- Coldest environment and minimum dissipation 63W the cryocooler temperature is much lower than -10℃, reaching -45.7℃. Freezing problem will not occur in the condenser of LHP even in -90℃, because of the low freezing point of propylene.

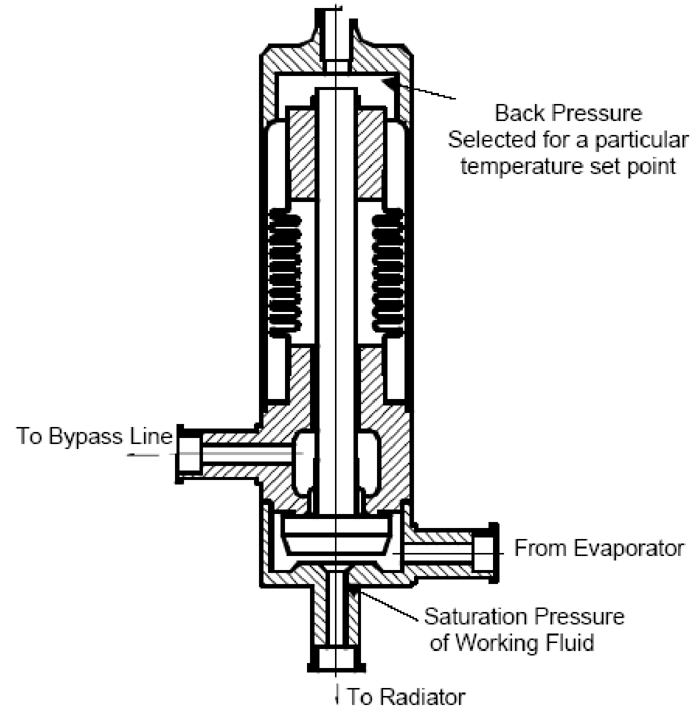


LHP-VALVE


By-pass line
Power
VALVE
Compensation
Chamber
(reservoir)
Vapour
line
Liquid
line
SOLAR
FLUXES
AMBIENT

By-pass Passive valve

- Valve stem into a bellows that divides the valve housing in two pressure compartments
- The pressure difference between the two compartments acts on the valve stem and initiates its movement into a closed/open position
- A compressed gas (Argon) creates the back-pressure on the upper side while the pressure in the other compartment is the sat. Pressure of the fluid
- The Back-pressure will be defined as to actuate the valve at a particular saturation pressure / temperature . Could be equivalent or lower the minimum cryo IF operating temp



LHP (propylene based) complete assembly