HyHP

Novel Hybrid Heat Pipe
for Space and Ground Applications

LP DESIGN OF PULSATING HEAT PIPES

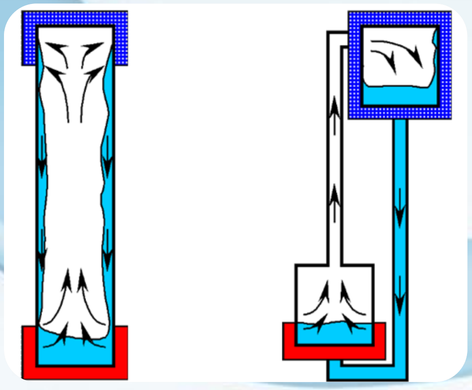
A NOVEL NON-EQUILIBRIUM LUMPED PARAMETER MODEL FOR TRANSIENT GRAVITY LEVELS

M. Manzoni, M. Mameli, C. DeFalco, L. Araneo, S. Filippeschi, M. Marengo

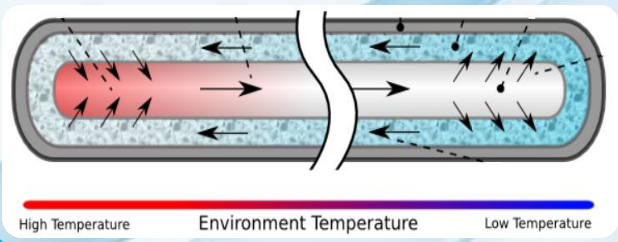
Universitatis Studiorum Bergomensis
University of Brighton
Politecnico Milano
In Supremae Dignitatis 1343
Technological Educational Institute of Piraeus
esa European Space Agency Agence spatiale européenne
agenzia spaziale italiana

INTRODUCTION

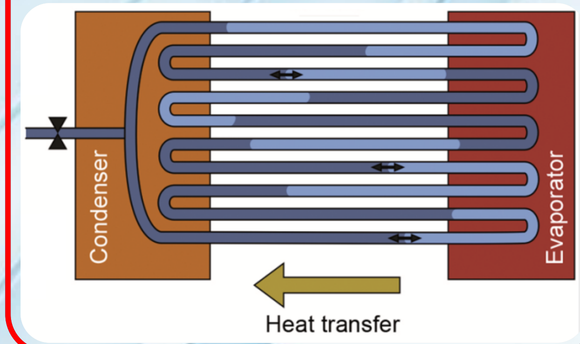
THERMOSYPHON



HEAT PIPE



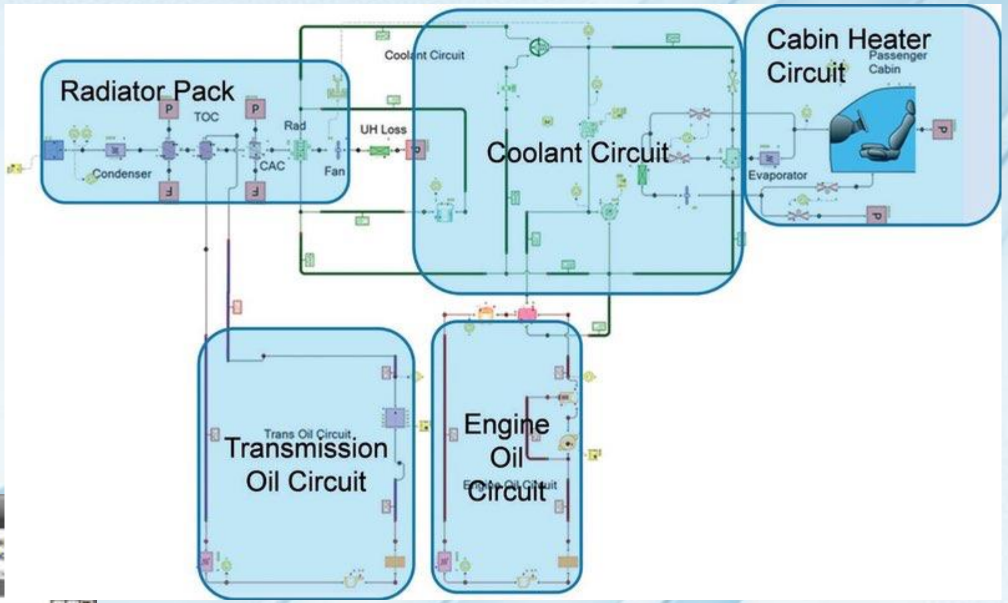
PULSATING HEAT PIPE

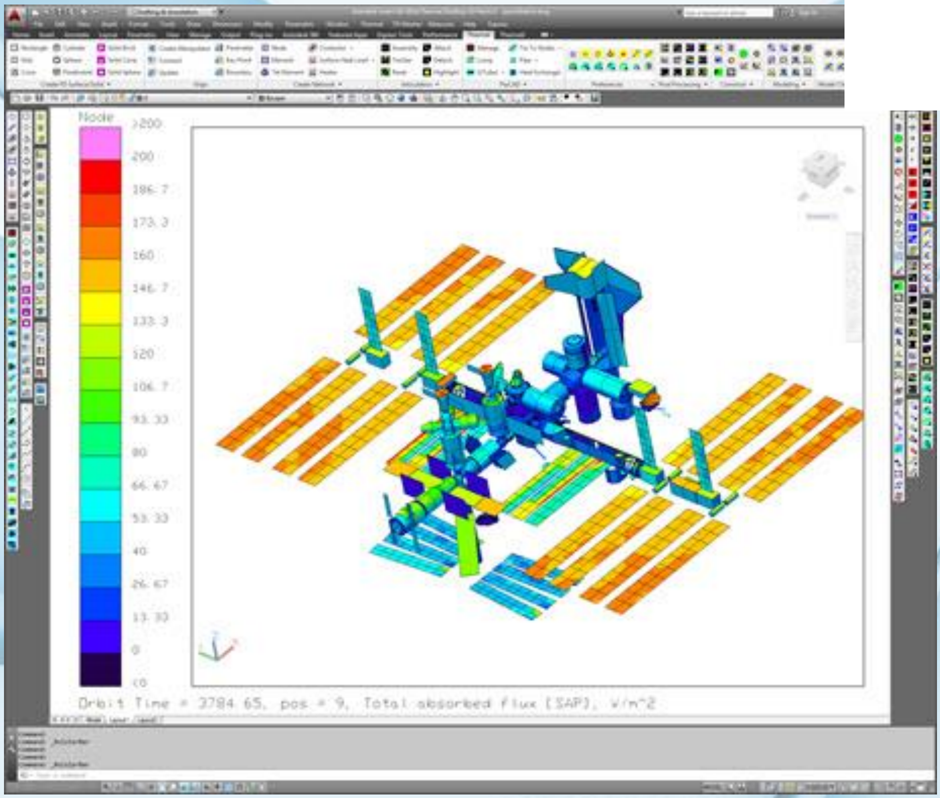


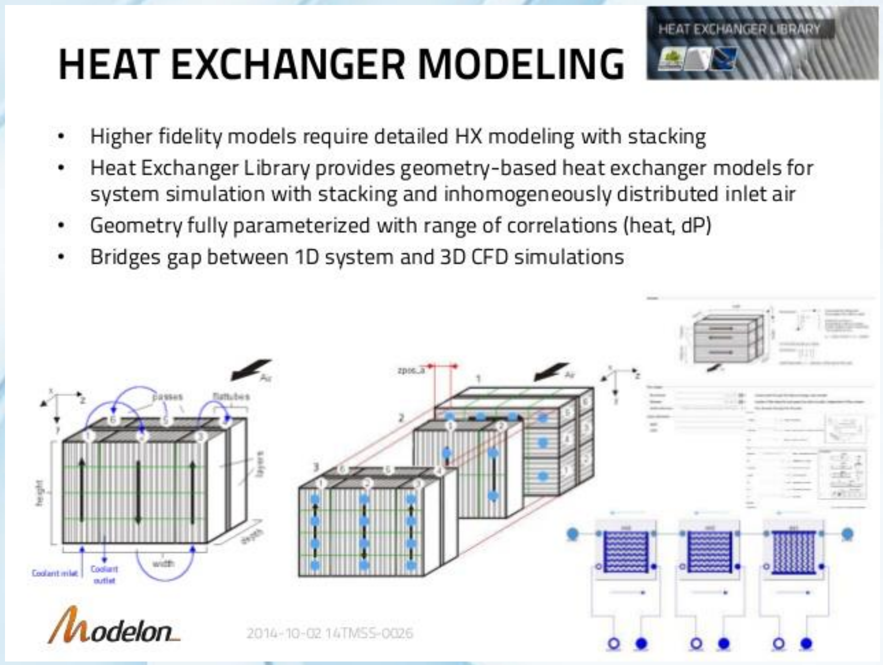
Pulsating Heat Pipes are the last frontier of the two-phase passive heat transfer devices. Due to their constructive simplicity and high heat transfer capability, PHPs could represent a new alternative to cooling systems in the near future. But in order to spread their industrial application in the most various fields, several open questions should find a proper answer. In this prospective, **experimental researches and validated numerical codes are essential to enlarged the present knowhow.**

LUMPED PARAMETER MODELING

THIS METHOD CAN CAPTURE THE HEAT AND MASS TRASNFER TRANSIENT BEHAVIOUR OF COMPLEX, FULL, LARGE SYSTEMS .







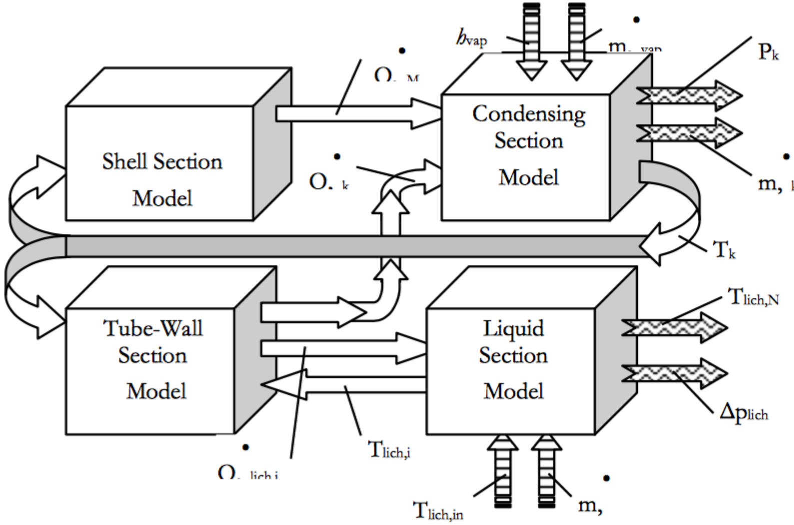


Figure 1: Functional model of shell-tube heat-exchanger

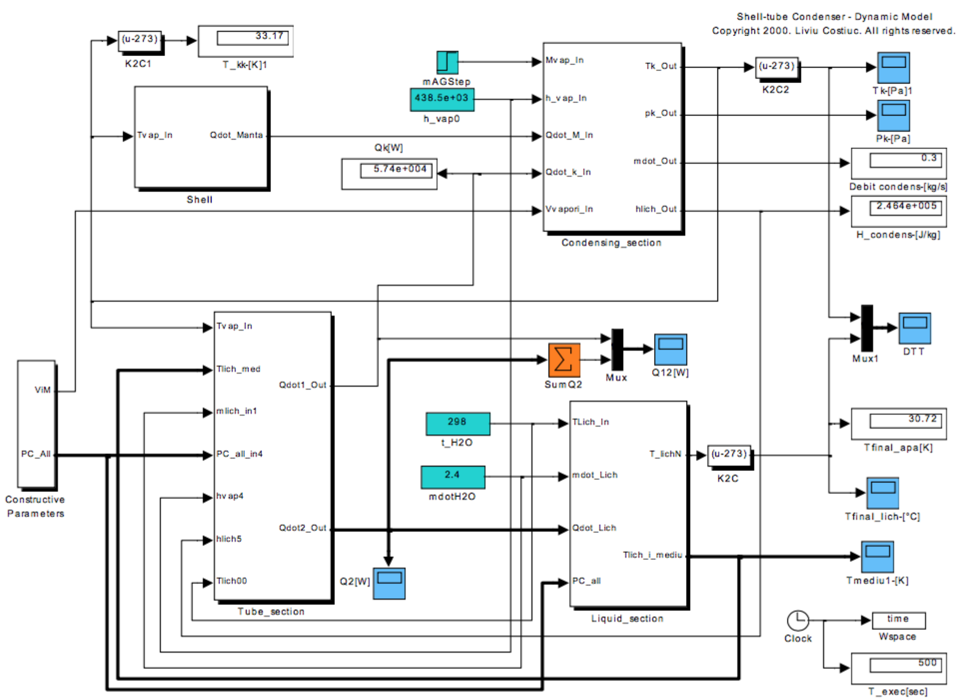
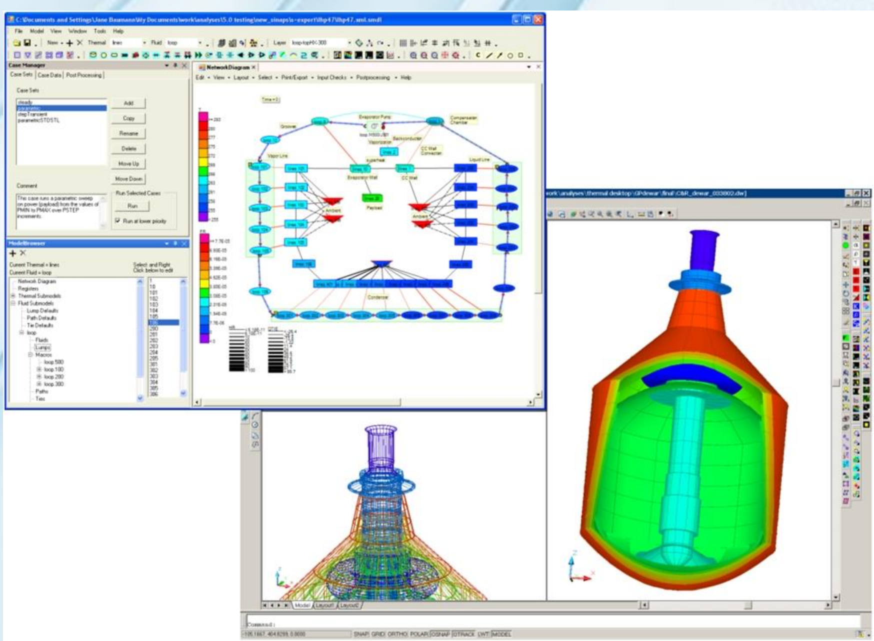


Figure 2: Simulink model for heat-exchanger

A LUMPED PARAMETER METHOD solves thermal and thermodraulic problems posed as finite elements, finite differences/volumes, lumped-parameter networks, or all three mixed within a single model. LPM models can be built using either a 3D/CAD-based system or using a 2D schematic-style sketchpad.

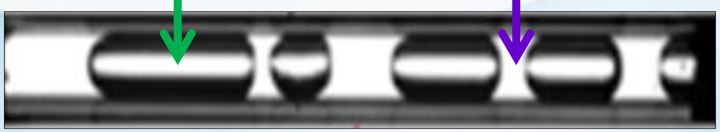


PULSATING HEAT PIPE

Thermally driven two-phase heat transfer device

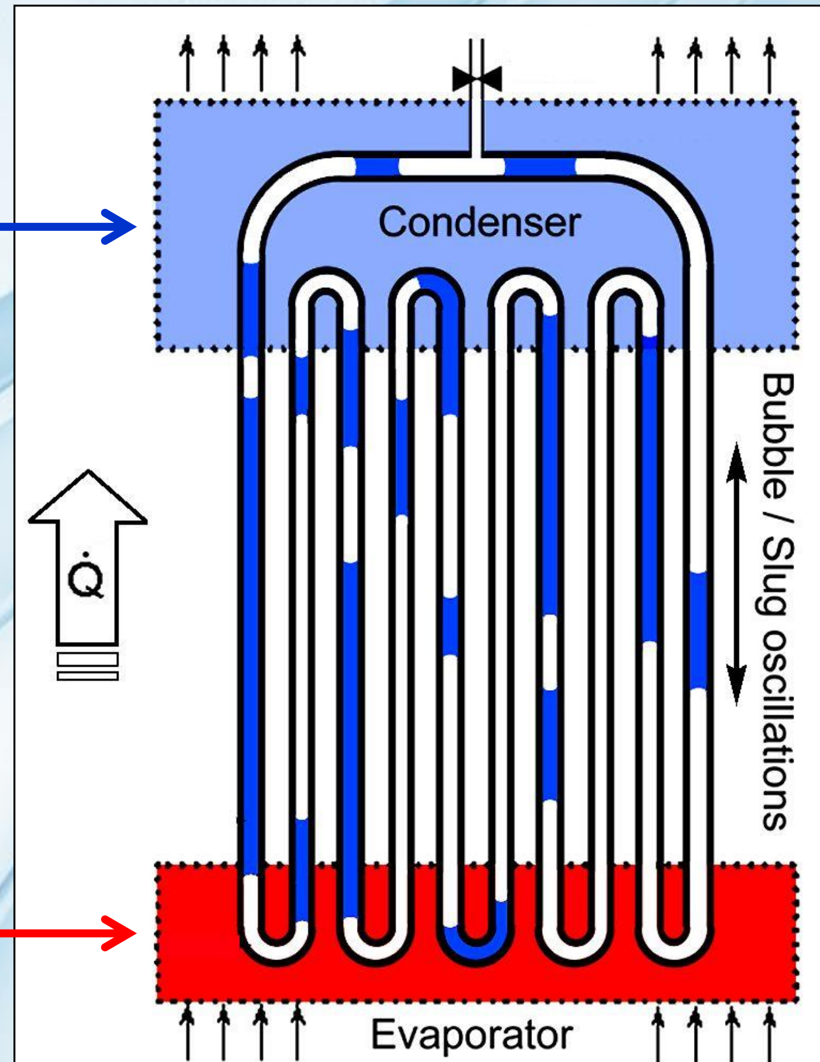
Capillary tube evacuated and partially filled with a working fluid

Alternation of
VAPOR PLUGS and LIQUID SLUGS



Heat power is provided to the EVAPORATOR section

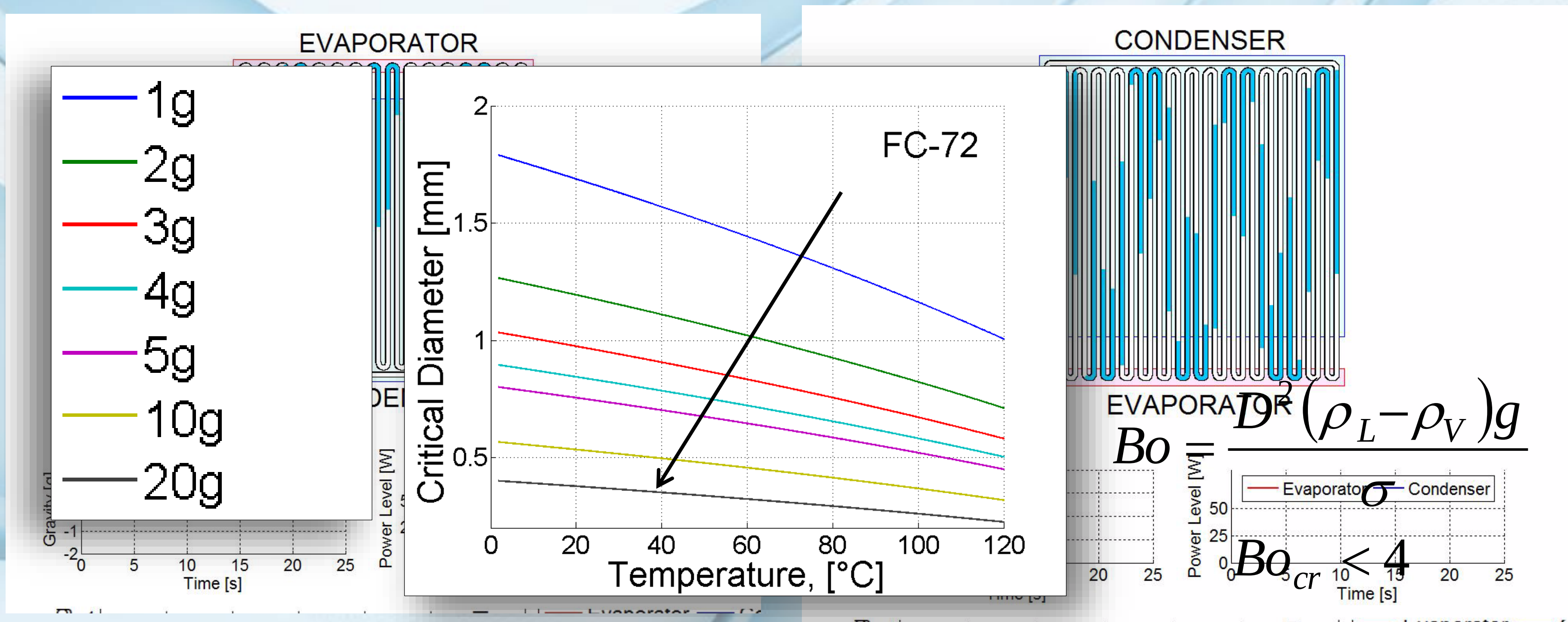
The heat is rejected to a cold source in the CONDENSER zone



INTRODUCTION

$$\left.\frac{D(mu)}{Dt}\right|_j = mg\sin\vartheta + A\Delta p - 0.5 f_\tau \frac{m}{d} u^2$$

LS Momentum Variation in Time	Gravity	VP Expansion and Compression	Friction Pressure Losses



$$Bo = \frac{D^2(\rho_L - \rho_V)g}{\sigma}$$

$$Bo_{cr} < 4$$

NUMERICAL MODEL

The developed numerical tool is an advanced 1D lumped parameters model able to compute both the steady and the transient performance of PHPs. This tool solves mass momentum and energy balances assuming confined operating regime a priori and a PHP of constant diameter.

NOVELTIES

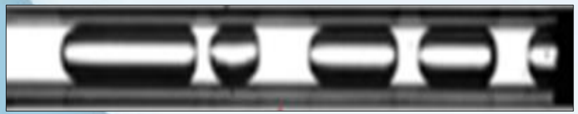
MODELING

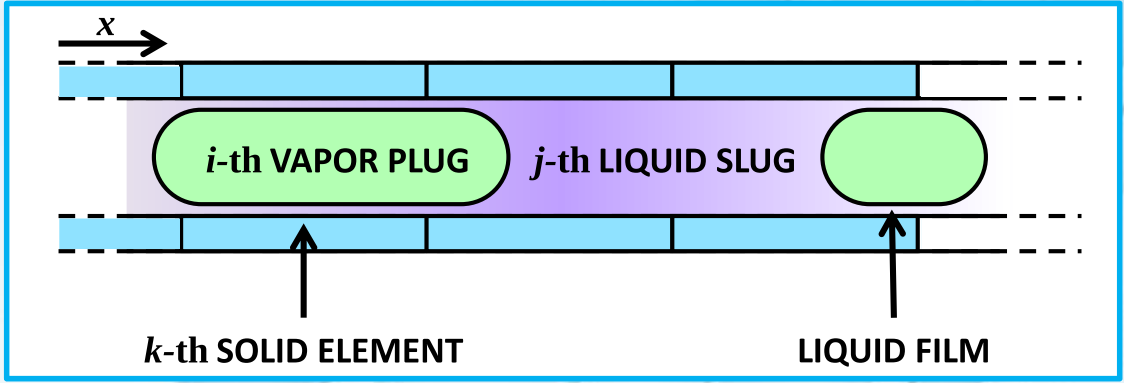
- **Vapor is treated as a real gas except during phase changes**. Thus its pressure is function of both temperature and density; density is calculated by definition.
- Vapor may exist in **saturated**, **super-heated** and **sub-cooled** conditions.
- **Heterogeneous evaporation and condensation** near the wall surface, **as well as homogeneous phase changes through the vapor/liquid interface are directly integrated within the code** by means of specific physical models.
- Since the liquid film dynamic has been neglected and classical semi-empirical correlations cannot be properly used for two-phase oscillating flows in mini channels**, a new correlation for the evaluation of the wall/vapor sensible heat transfer coefficient has been proposed and tuned against experimental data**.

NUMERICAL

- **The numerical model has been implemented in GNU Octave,** a licence-free software oriented to and optimized for scientific calculus.
- Advanced numerical techniques and specific numerical schemes have been adopted to allow **fast simulations** and to guarantee **numerical accuracy and stability**.

NUMERICAL MODEL





The SOLID MODEL describes the thermal behaviour of the external tube by means of an Eulerian numerical approach since solid elements are fixed in time.

The FLUIDIC MODEL describes the fluidynamics and the thermal behaviour of the internal vapor and liquid elements by means of a Lagrangian numerical approach since fluidic elements are moving in time. In addition, slugs and plugs may change length and mass due to phase changes.

SOLID/FLUID COUPLING is the last important block. From a numerical point of view an embedded **funct**[...]**mmunication between the adopted Euler**[...]**ngian appr**[...] From a physical point of view solid and fluidic domains are related by means of the **heat** [...] **wall and fluid**[...]

The developed numerical model requ[...] modynamic, operative and numerical parameters. The unknown inputs have been assumed in feasible ranges and tested by means of sensitivity analysis.

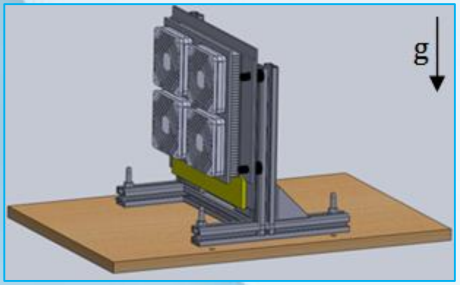
Heterogeneous Phase Changes
- MASS BALANCE
- ENERGY BALANCE

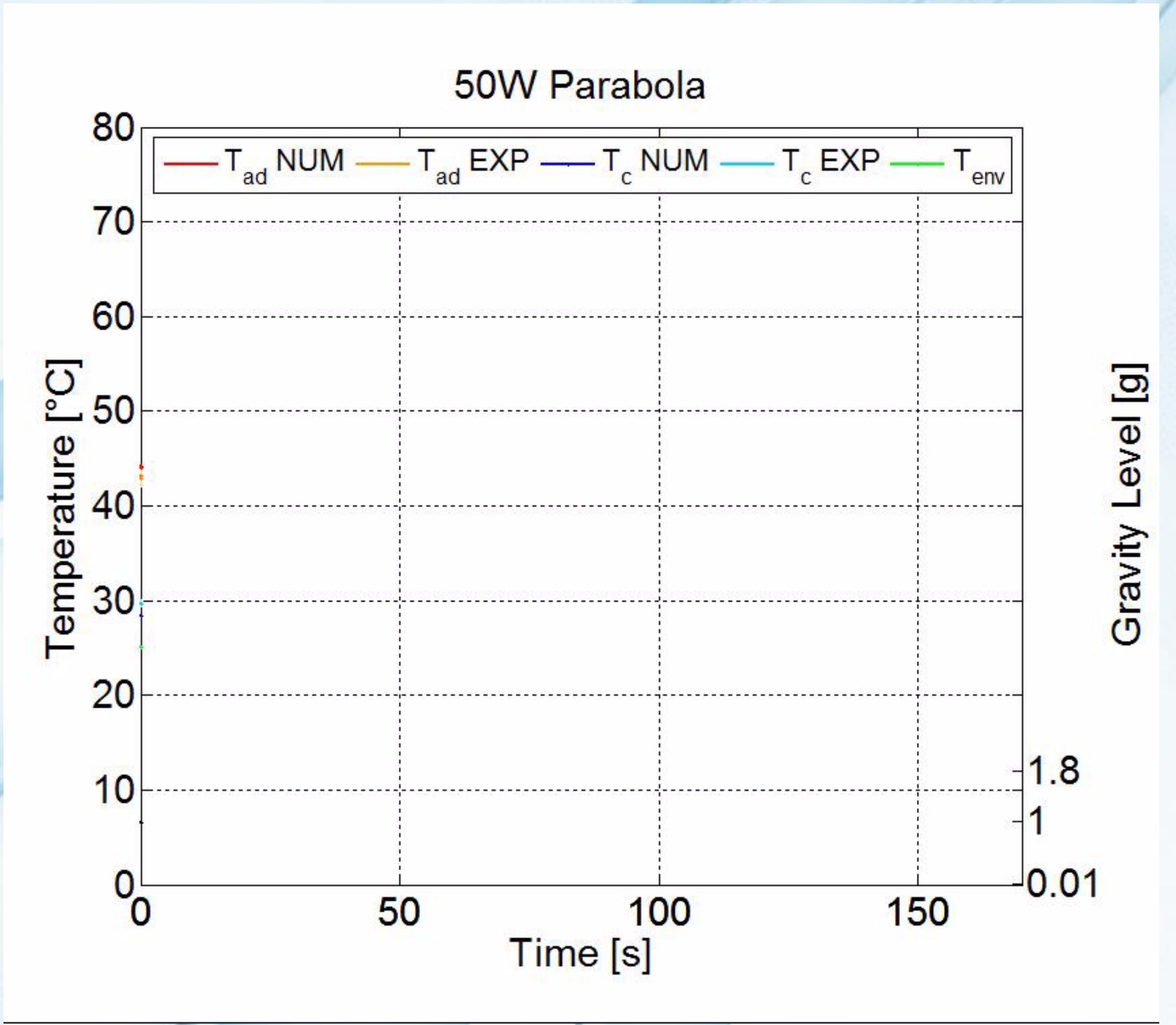
Homogeneous Phase Changes
- MASS BALANCE
- ENERGY BALANCE

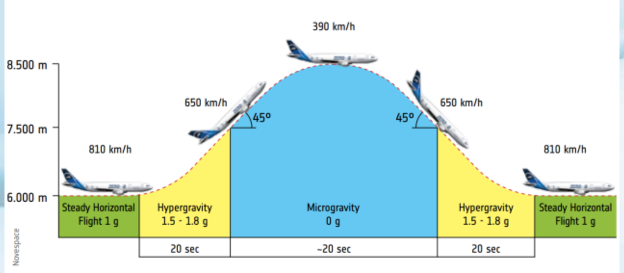
All the other phenomena
- ENERGY BALANCE
- MOMENTUM EQUATION

t → $t+\Delta t$

MICRO-GRAVITY RESULTS – 0.01g

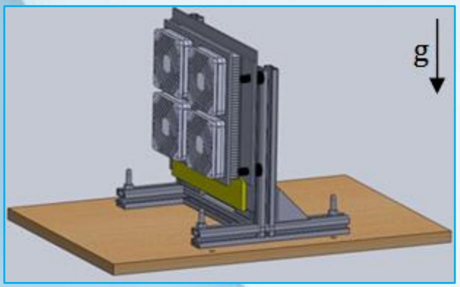


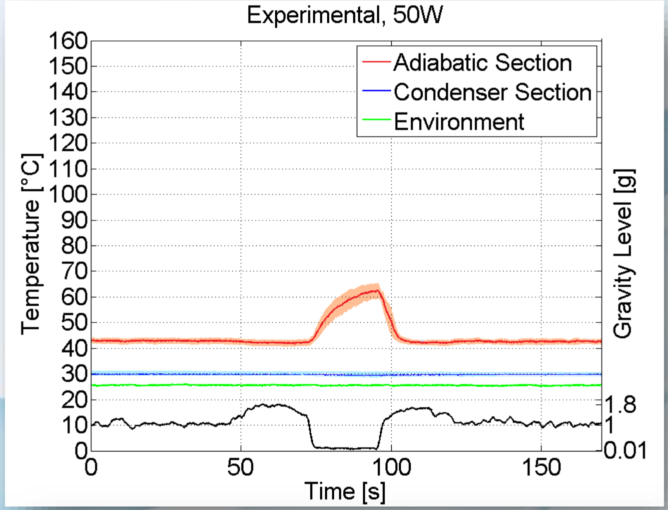


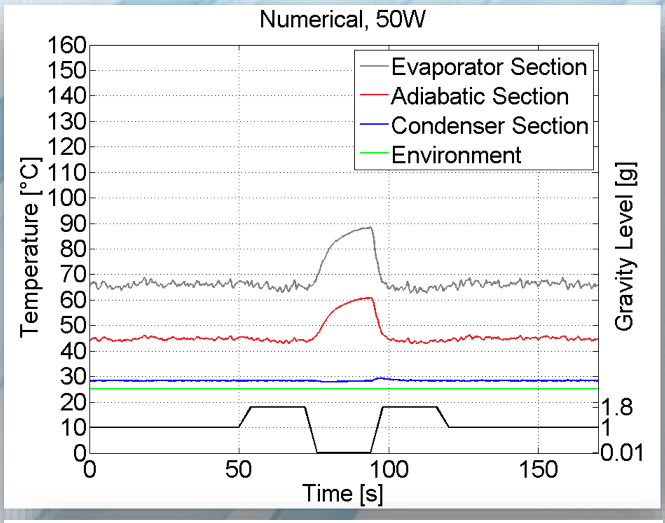


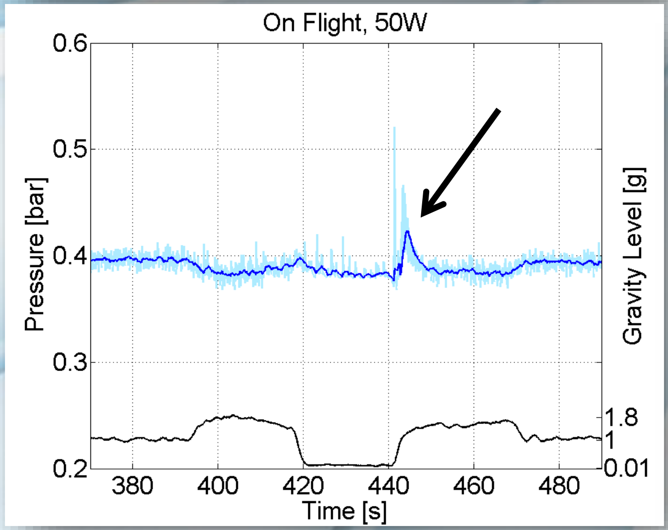
CODE VALIDATION

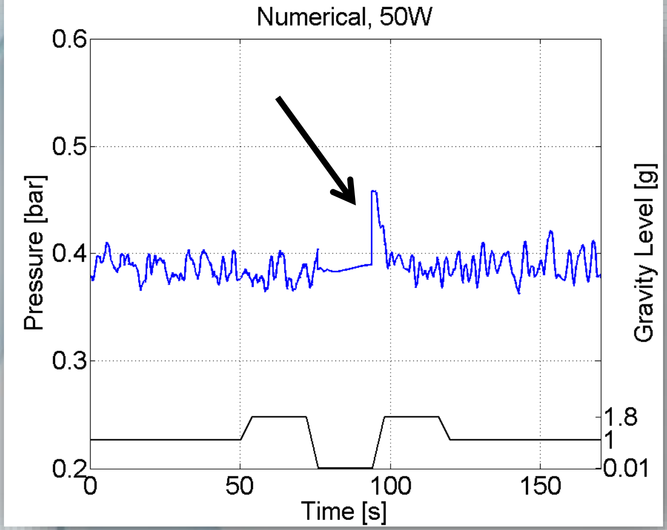
HYPER-GRAVITY RESULTS – UP TO 2g











Conclusions

The proposed work has **two goals**:

(1) from the **experimental** point of view, it aims to provide *information about the combined effects of gravity and heat input on PHPs performances*;

(2) on the **numerical** side, it heads for the development of a *numerical tool able to simulate the thermal-hydraulic behaviour of PHPs in steady as well as in transient operative conditions*.

CONCLUSIONS

A new, advanced, 1D, lumped parameter numerical code has been proposed and validated against experimental data. The main originalities lay in the suppression of the standard assumption of saturated vapor plugs as well as in the consequent embedding of heterogeneous and homogeneous phase changes. Being able to reproduce with high accuracy both the stationary and the transient behavior of PHPs in several operative conditions and for different gravity levels, **at the moment it represents one of the best numerical tool findable in literature**.

Future Developments

- The **artificial numerical damping detected in horizontal mode** should be mitigated.

- The **dynamic of the liquid film** should be accounted for by means of devoted sub-models.

- The correlation used to estimate wall/vapor sensible heat transfer coefficient should be validated against experimental data coming from various fluids (different from FC-72) and various filling ratios (different from 0.5).

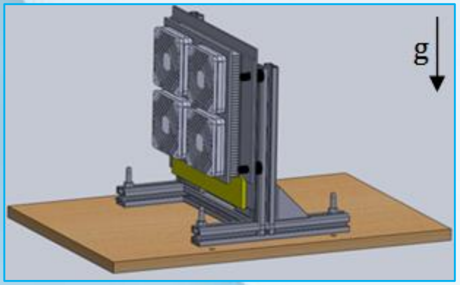
- The **transition between different flow patterns** should be studied and implemented in devoted sub-models in order to surpass the strong common simplification of slug flow and being able to detect also **critical operative conditions** and **operative limits**.

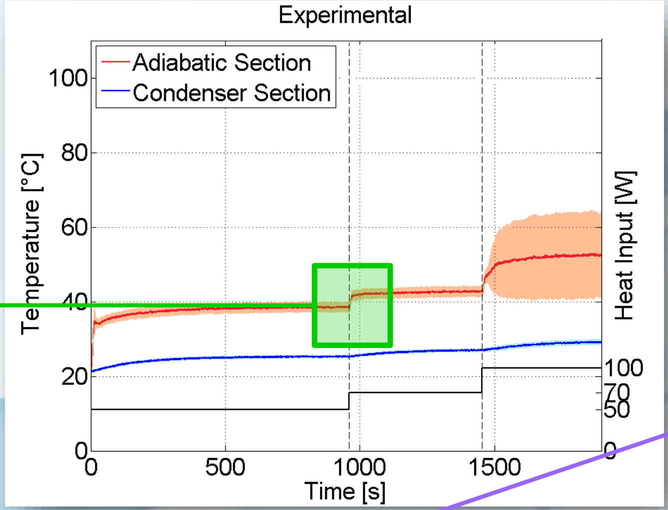
THE END….

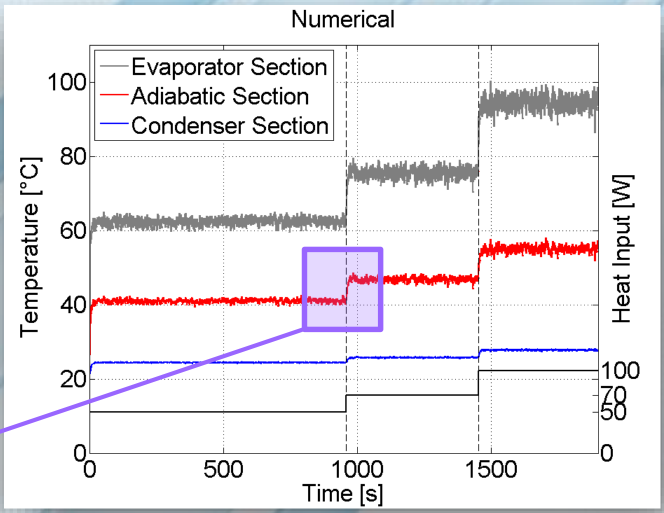
THE BEGINNING….

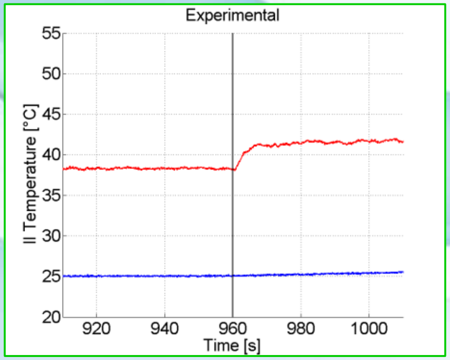
CODE VALIDATION

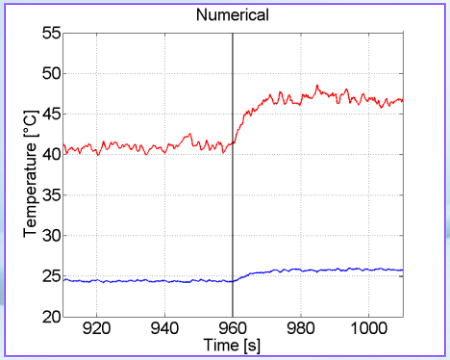
GROUND RESULTS – 1g





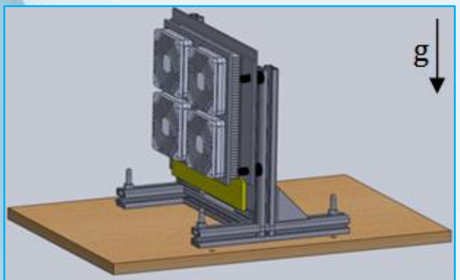


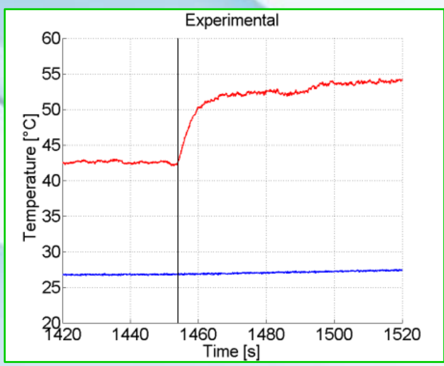


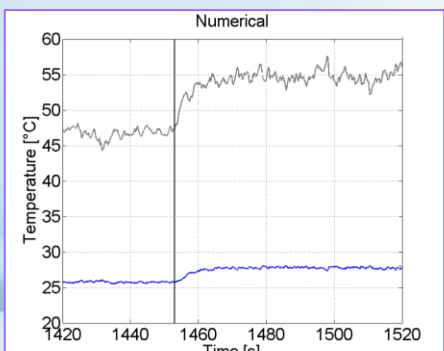


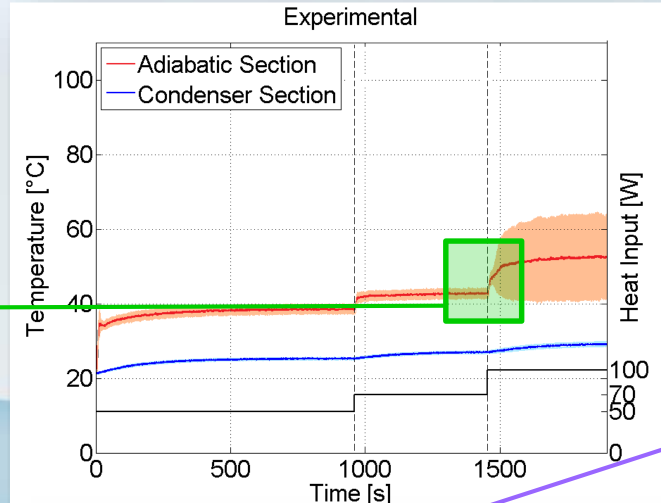
CODE VALIDATION

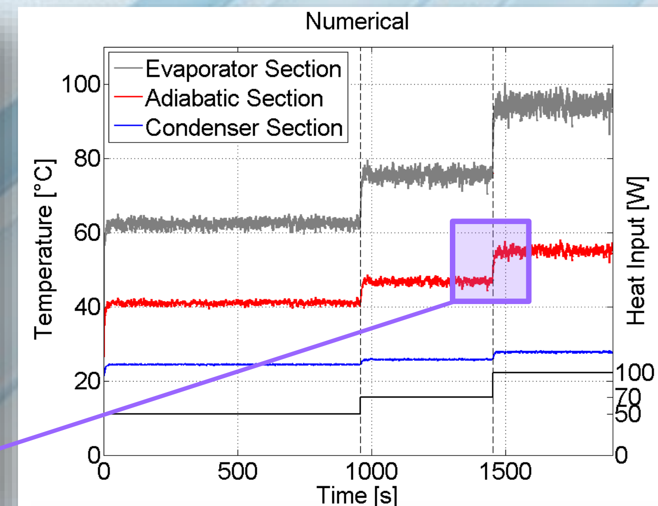
GROUND RESULTS – 1g

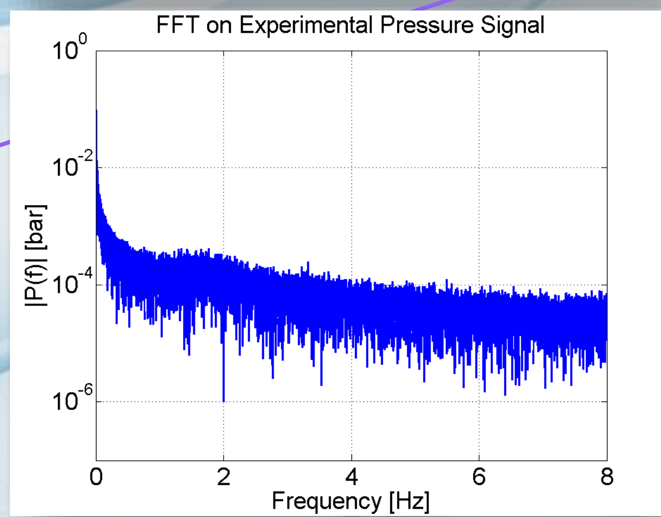


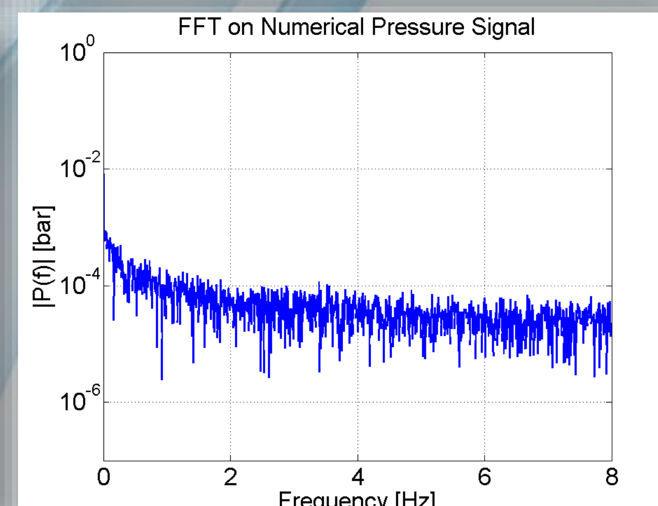












Conclusions

A complete characterization from micro to hyper-gravity conditions (0.01 - 20g) of a lab scale PHP has been proposed, confirming that, in a 2D layout with a relatively high number of channels, **gravity plays an important effect on the PHP thermal behavior.**

In vertical mode, **the absence of gravity drastically reduces the thermal performance of the device**, while augmented gravity levels may either assist or inhibit the flow motion.

For each power input there is a gravity value below which hyper-gravity yields to better thermal performance, over which it leads to different kinds of instability.

If the fluid pumping forces resulting from the heating power can compete with the acceleration forces the system only undergoes local frequent stopover phenomena (**Transient Thermal Instability**), otherwise the wall temperatures increase and settle to higher levels (**Thermal Crisis**).

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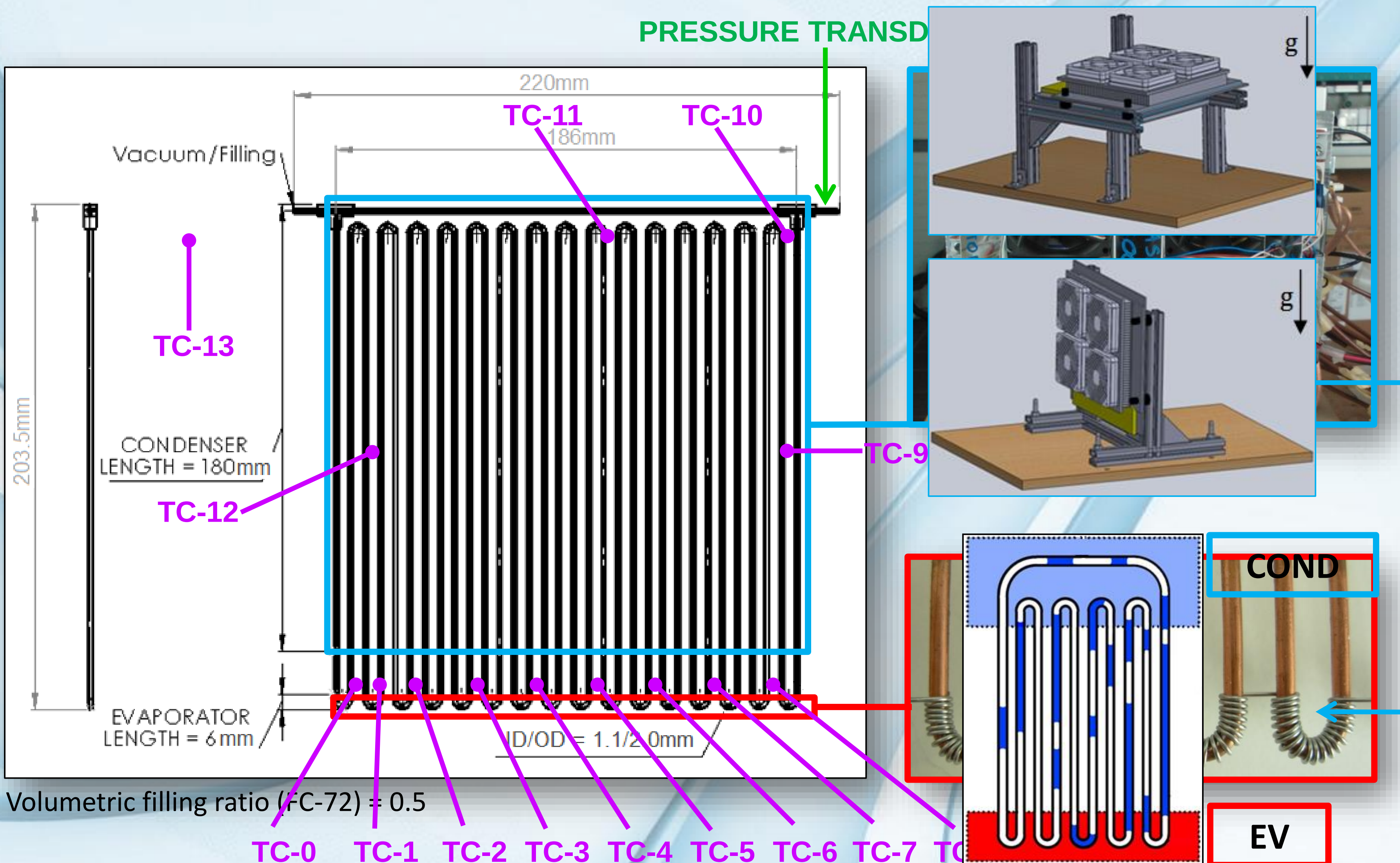
EXPERIMENTAL SETUP

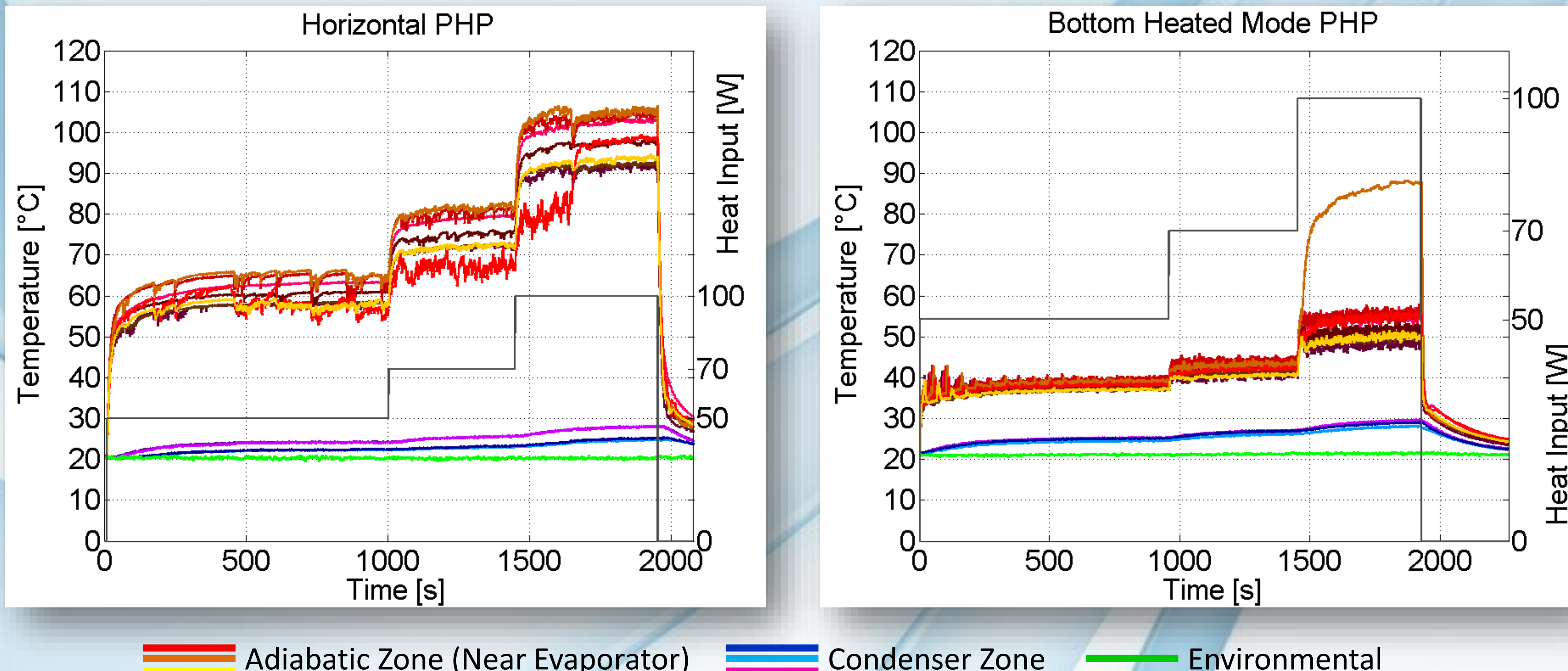


Volumetric filling ratio (FC-72) = 0.5

CASE 0: GROUND TESTS

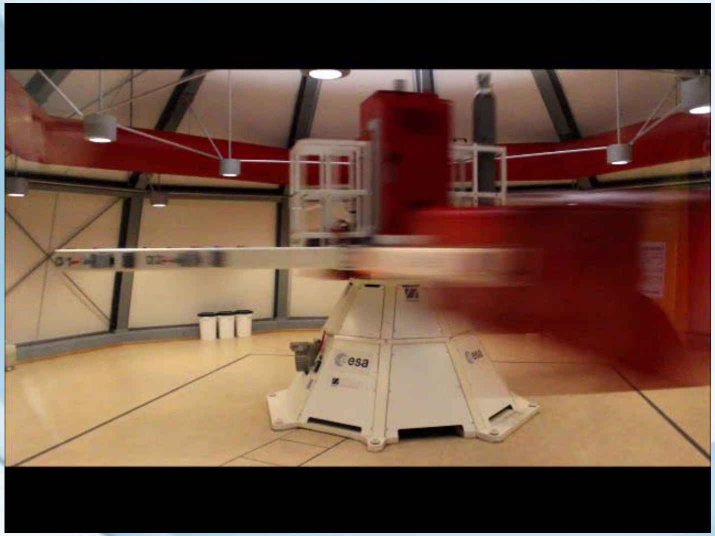
University of Brighton

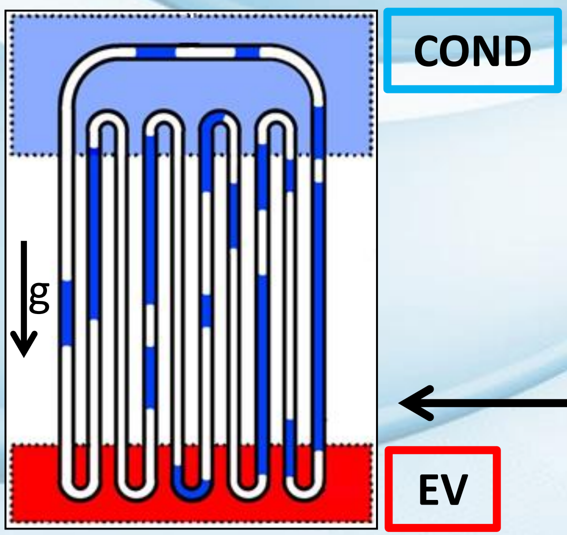
GROUND RESULTS – 1g

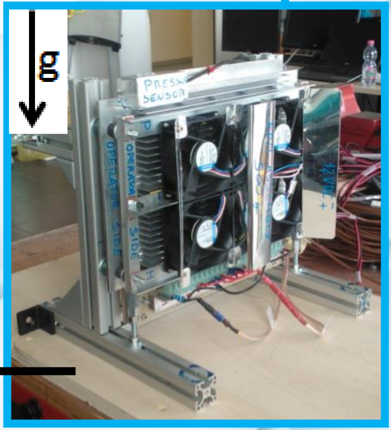


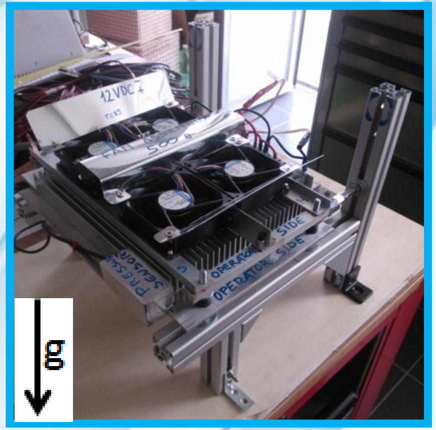
On ground, vertical and horizontal orientations show very different behaviors confirming that, in a perfect 2D layout with a relatively high number of channels, **gravity plays an important effect on the PHP thermal behavior** since it improves the fluidic circulation. The thermal resistance of the horizontal PHP is about two times higher than the one estimated for the vertical device.

CASE A: HYPER-GRAVITY





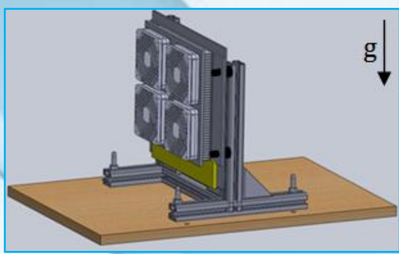


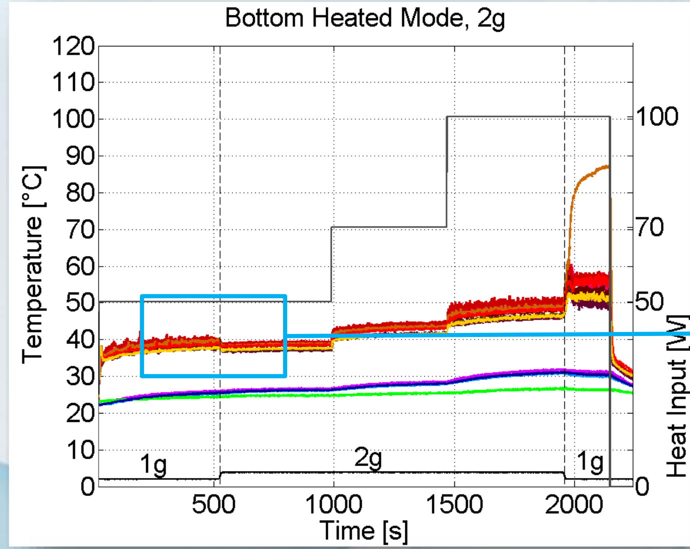


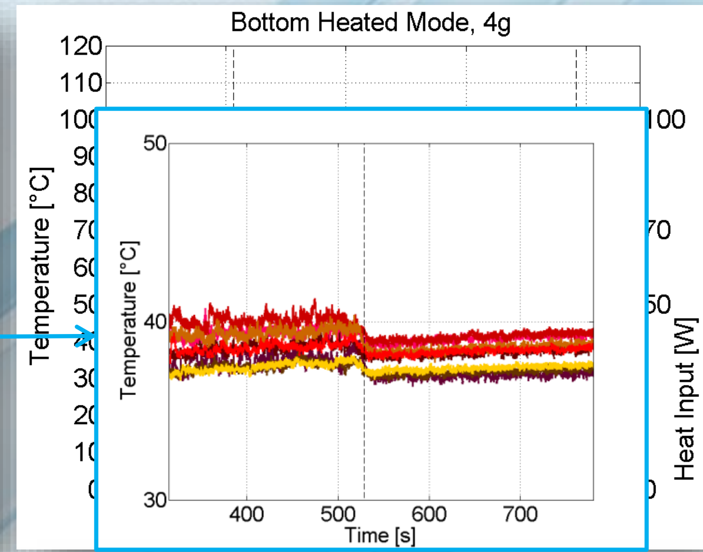
PHP

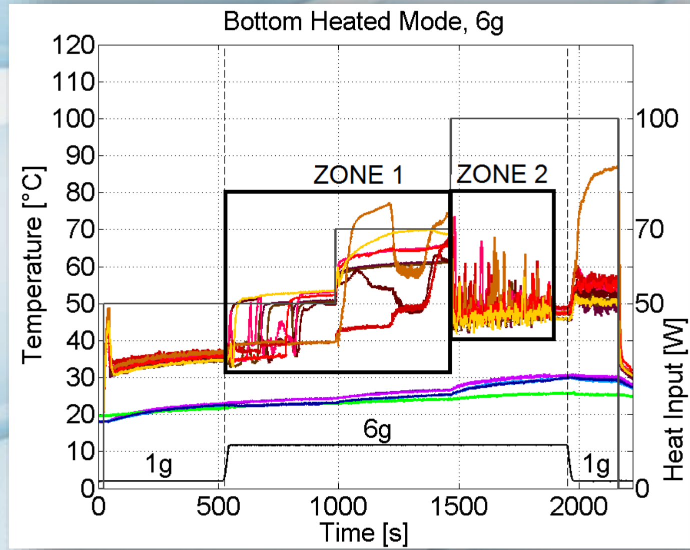
DAQ

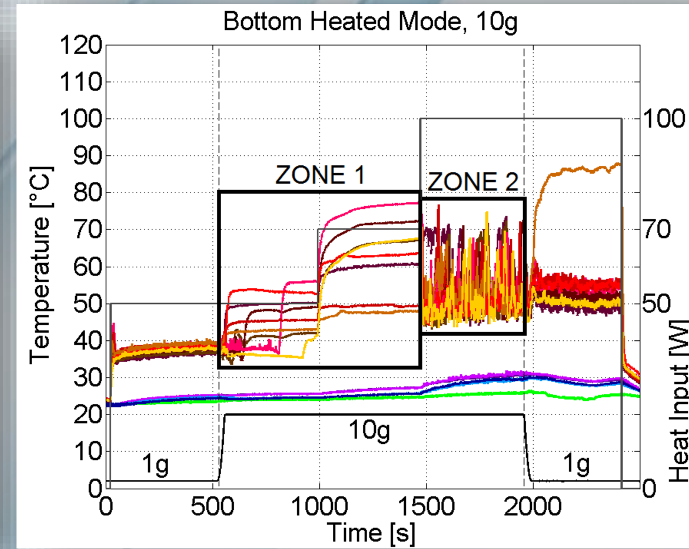
Case A: Hyper-Gravity









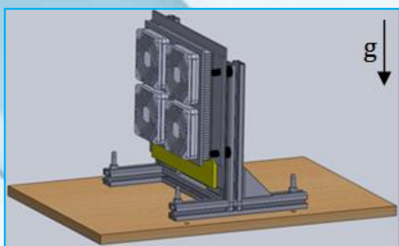


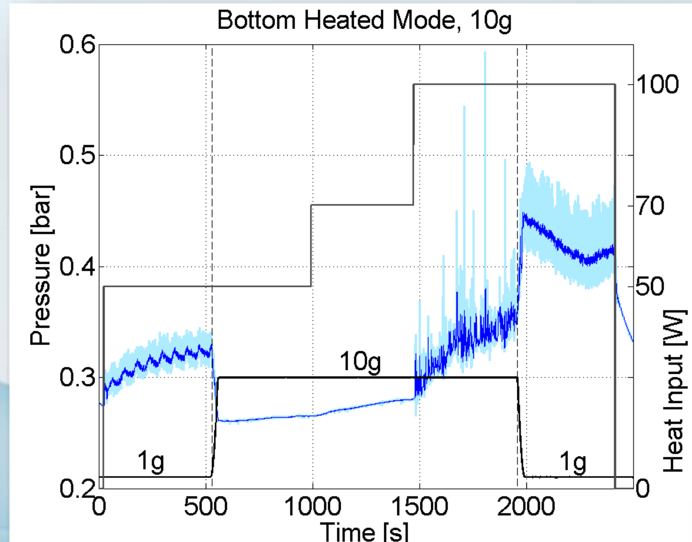
Adiabatic Zone (Near Evaporator)

Condenser Zone

Environmental

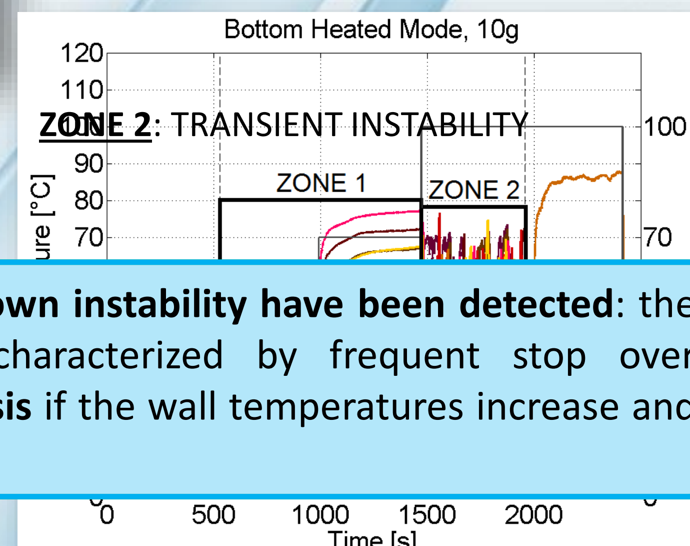
CASE A: HYPER-GRAVITY





ZONE 1: THERMAL CRISIS

ZONE 2: TRANSIENT INSTABILITY



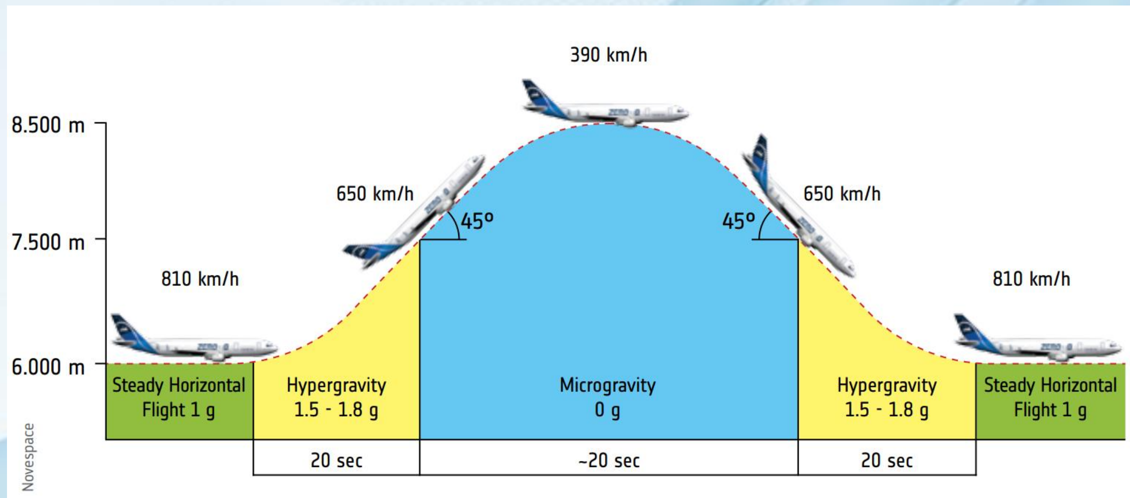
Adiabatic Zone (Near Evaporator)

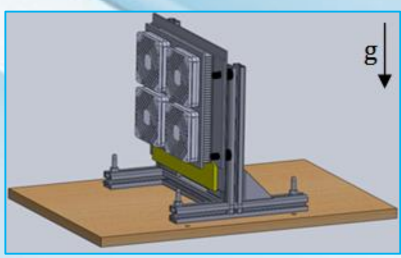
Condenser Zone

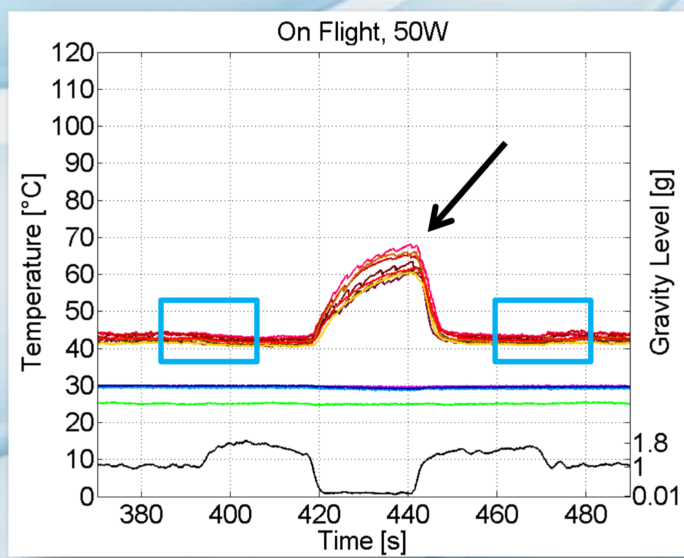
Environmental

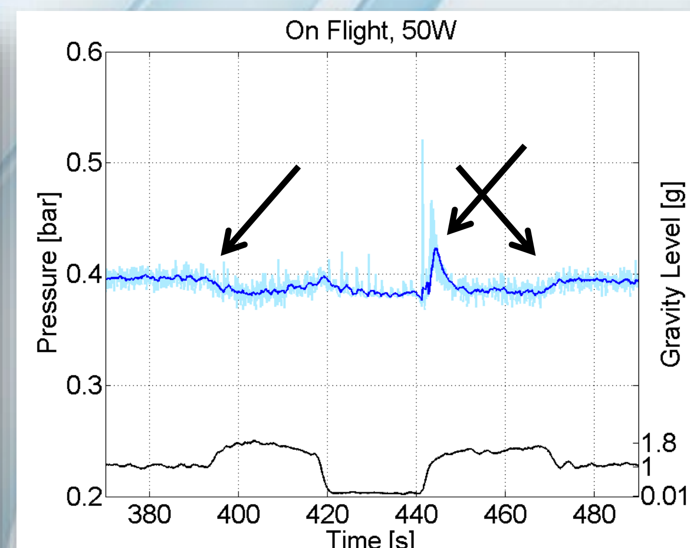
Two different kinds of yet unknown instability have been detected: the **transient thermal instability,** characterized by frequent stop over phenomena, and the **thermal crisis** if the wall temperatures increase and settle to a higher levels.

CASE B: MICRO-GRAVITY









Adiabatic Zone (Near Evaporator)

Condenser Zone

Environmental