Appendix L

LHP module for ESATAN & THERMICA thermal solvers, dedicated to system level thermal analyses

Frédéric Jouffroy
(EADS Astrium, France)

Anne-Sophie Merino
(Thales Alenia Space, France)

Amaury Larue de Tournemine
(CNES, France)

Abstract

A Loop Heat Pipe (LHP) is a key two-phase technology for reaching, at low mass and cost, the heat transportation capability needed by recent advanced space missions, either in terms of large amounts of heat to be transferred (more than 10 kW) or of reduced temperature gradients between dissipative units and the corresponding radiator area.

Although LHP technology is now available to be included in future systems, its practical use for industrial projects is in practice related to the possibility of predicting the thermal behaviour and mutual thermal interactions between LHPs and a space system. The objective of a LHP software module is to provide a sufficient LHP model for system analyses that can be easily plugged into usual thermal models developed by European space industry (ie based on Esatan and Thermica thermal solvers).

A LHP Module has been developed through a partnership including ESA and CNES agencies, and EADS Astrium and Thales Alenia Space (TAS) industrial companies. EADS Astrium was mainly in charge of the software development while TAS efforts were focused on validation.

The LHP Module is based on the use of the standard ESATAN $ELEMENT feature such that it can be directly interfaced as a submodel with any existing model. A standard simple evaporator model is used, involving 3 or 5 thermal nodes depending on data provided by the LHP supplier. Tubing (vapour line, condenser and liquid line) modelling developed includes thermal and hydraulic aspects. The meshing is to be defined by the thermal engineer according to and consistent with the one existing in the corresponding system model (radiators and panels). Several different tubing sections can be set for liquid and vapour lines in order to take into account for instance the different flexible sections for a deployable radiator; it is also possible to model multi-condensers with up to 5 parallel branches.

The LHP software module is mainly dedicated to transient problems, allowing to predict LHP stop and start events. Steady-state situations can in practice be handled by running stabilized transient cases. In order to ease integration of LHPs within system models, the different LHP components (fluid used and hardware parts: evaporator, condenser, vapour and liquid line hardware) and assembly are defined in separate external files to be referenced in the system model; this reduces the changes to be applied to the system model as much as possible and enables the construction of libraries of component files for future reuse.

Validation of the LHP module has been performed through comparison of temperature predictions with measurements for different hardware and configurations, including flight measurements, such as Inmarsat-IV, Delphrad and Com2plex. Correlation less than 5° could be obtained in many cases.

The LHP module is available for the European thermal space community as a ”black box” tool compatible with available Thermisol v4.3.3 and the next version of Esatan planned to be released by end 2010.

LHP Module for ESATAN & THERMICA thermal solvers, dedicated to system level thermal analyses

Frédéric JOUFFROY, EADS Astrium

Anne-Sophie MERINO, Thales Alenia Space

Amaury LARUE DE TOURNEMINE, CNES

24th European Workshop on Thermal and ECLS Software

16-17 November 2010

Agenda

- Introduction
- Software presentation
- Software validation
- Availability

2

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3

Context

- LHP : An emerging technology for heat transfer
- Need for a tool able to predict system-LHP thermal interactions and behaviour by using European usual space thermal software
  - Esatan solver
  - Thermica solver
- Involvement of agencies & prime contractors
  - CNES
  - ESA
  - ASTRIUM
  - TAS

4

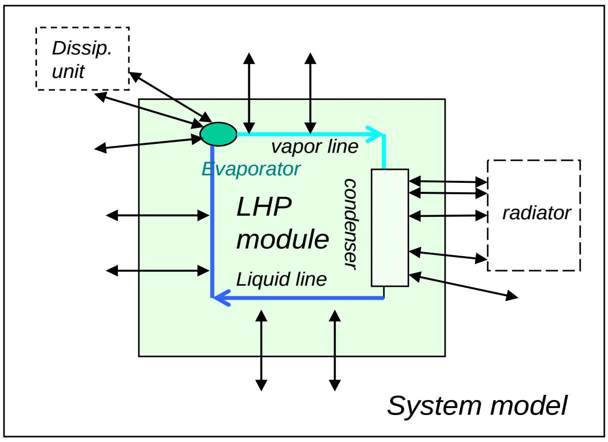
Modelling capabilities

- LHP behaviour
  - Thermo-hydraulic heat transfer
    - Tubing nodes+fluid nodes modelling, mass flow prediction
    - All heat transfer configurations managed (cooling & heating)
      - Vapour & liquid 1-phase heat transfer
      - 2-phases vapour/liquid heat transfer.
  - LHP start & stop prediction (unit switch on/off)
    - Minimum/maximum acceptable transferred power
    - Evaporator-reservoir gradient
- LHP configurations
  - Evaporator: designs supported through generic simplified modelling
  - Vapour line: Different tubing sections (flexible, rigid)
  - Condenser: Multiple branches
  - Liquid line: Different tubing sections

5

Interaction with system model

- Several LHPs can be used within a system model
- Any radiative/conductive interface can be modelled
- Tubing meshing (vapour line, condenser, liquid line) to be defined according to system model need



Interface modelling has a strong influence on results !

6

Implementation concept

- Esatan & Thermica solver compatibility:
  - LHP designed as a $ELEMENT submodel to be plugged into system model
    - → No limitation on number of LHPs used but impact on CPU time
    - → No limitation on interface definitions (couplings LHP-model)
- Generic tool adaptable to various LHP designs
  - LHP HW and fluid definition done through external files
- 'Blackbox version' for delivery to subco & partners
  - Compiled version protects confidential source code
  - Reduces source code length
    ⇒cuts pre-processing & compilation duration when many LHPs are plugged into system model

7

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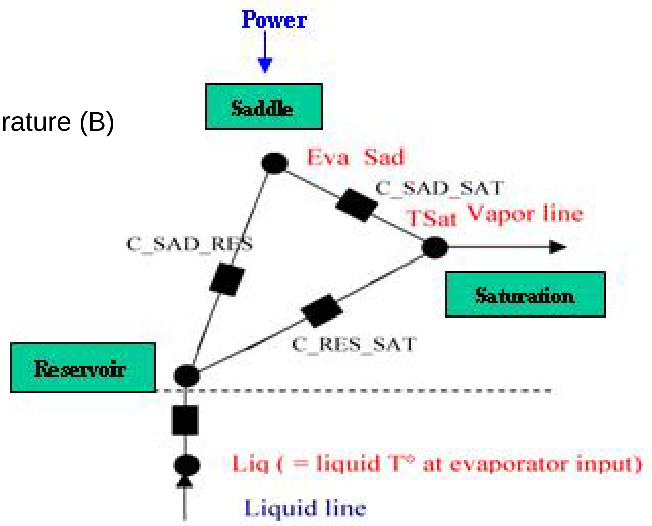
8

Evaporator modelling

- Evaporator
  - Built-in reduced definition : 3 nodes/couplings only used for computation
    - Reservoir (D)
    - Evaporator body (D)
    - Fluid saturation temperature (B)



  - Possible 5 nodes/couplings definition: internal conversion to 3 nodes

9

LHP definition & use

- Hardware components
  - One file per LHP item (Evaporator, vapour line, condenser, liquid line, fluid)
    - Geometrical & physical properties
- Component assembly:
  - *LHP configuration integration file*
    - Calls for Hardware component files
    - Defines meshing for condenser &lines: nb of nodes, regular or not
    - Global parameters: total fluid mass
    - Initial conditions: temperature & heating
- Use in system model: $ELEMENT
  - Default parameter values can be superseded ($substitutions)
    - Data structure dimensions
    - Debug mode for file read
    - …

```
$MODEL LMAIN
$MODEL LHP1
$ELEMENT LHP
$SUBSTITUTIONS
…….
```

10

Tool execution

- Transient conditions
  - Time step must be compatible with LHP time constant ≈ a few seconds
    - ⇒***Potential critical computation duration for large system models***
    - ⇒ Need for improving TMM computation speed
      - Thermica solver spatial time step variation (Multi-step capability)
      - …
- Steady-state conditions
  - Intrinsic LHP model instability
  - Cyclic convergence (repetitive min & max TSAT value for LHP node) is automatically detected when occurring ⇒ Warning + early stop of execution.
    - ⇒ ***run the model in 'stabilized' transient mode***

11

LHP Operation reporting in *.out* file:

- Physical characteristics & SW operation reporting
  - *to be done in system model:* CALL LHP1:OUTPUTLHP

```
|----------------------------------------------------------
|                 MODEL CONTROL PARAMETERS
| CURRENT INSTANT (TIMEM)                    :      89956.00
| CURRENT TIME STEP (DTIMEU)                 :          2.00
| NUMBER OF ITERATIONS (LOOPCT)              :             4
| CONVERGENCE CRITERIA (RELXCC)              :    -0.404E-05
| NUMBER OF LHP OPERATION EMITTED WARNINGS   :            11
| NUMBER OF LHP START/STOP EVENTS            :             3
|----------------------------------------------------------
|               LHP THERMAL CHARACTERISTICS
| HEAT INPUT (W)                             :         1.195
| HEAT TRANSPORT (W)                         :         1.482
| FLUID SATURATION TEMPERATURE (°)           :         23.20
| EFFECTIVE SUBCOOLING (°)                   :         10.32
| EVAPORATOR CONDUCTANCE saddle-fluid (W/K)  :         10.22
| CONDENSER CONDUCTANCE fluid-saddle (W/K)   :          0.08
| TOTAL LHP CONDUCTANCE saddle-saddle (W/K)  :          0.08
| ...
```

- All changes in condition status are output
  - ⇒Start/Stop events tracked

```
*** LHP INITIAL OPERATION STATUS AT TIME =  5.0  ***
 LHP defined in submodel LHP1 should OPERATE
     Power at evaporator=  194.1   >= [min op] specified power=  0.0
     Power at evaporator=  194.1   <= [max op] specified power=  500.0
     Δ (saddle,reservoir)=  57.05 - 43.6 = 13.4 >= Min. op. Δ =1.0E-02
     Total pressure head in loop=  5134.5  <= Max.sustainable evaporator
pressure head=  50000.0

*** LHP OPERATION EVENT ***
 LHP defined in submodel LHP1 should STOP around TIME=  20.0
   Insatisfied conditions :
     Power at evaporator=  -14.002  <  [min op] specified power=  0.0
```

12

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13

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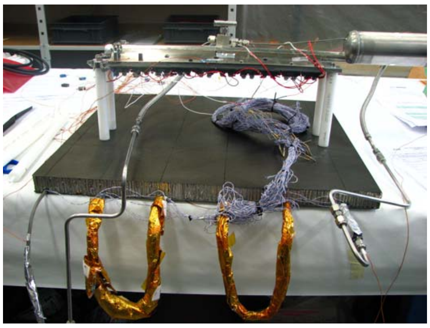
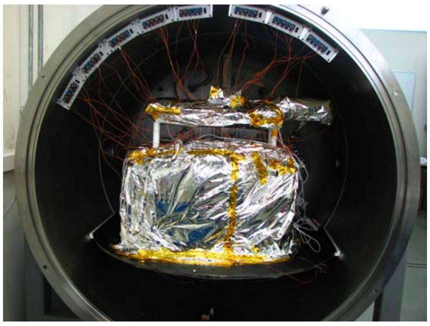
LHP2 radiator test case

- Ground vacuum test
  - LHP² evaporator hardware
  - Condenser tubing embedded in radiator panel
  - Radiator facing temperature controlled cold plate

TEST



MODEL



14

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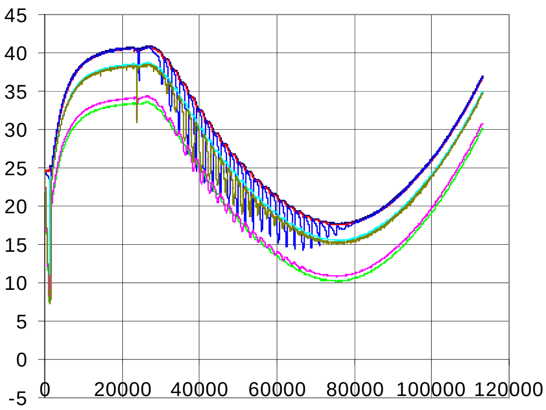
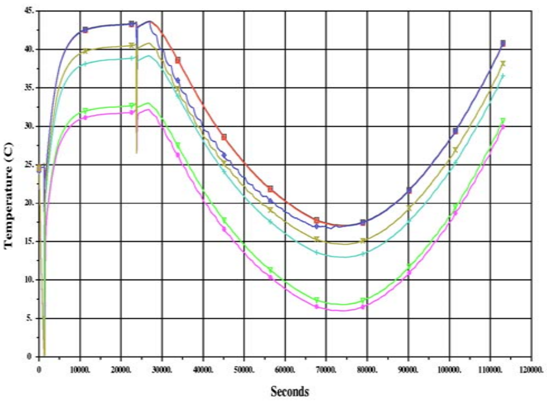
LHP2 radiator test case

- Correlation to test results performed
  - Constant power source 50W, cold plate: -10→-55→-10 °C
  - Good simulation of specimen behaviour
  - Correlation < 5°C

TEST



MODEL



15

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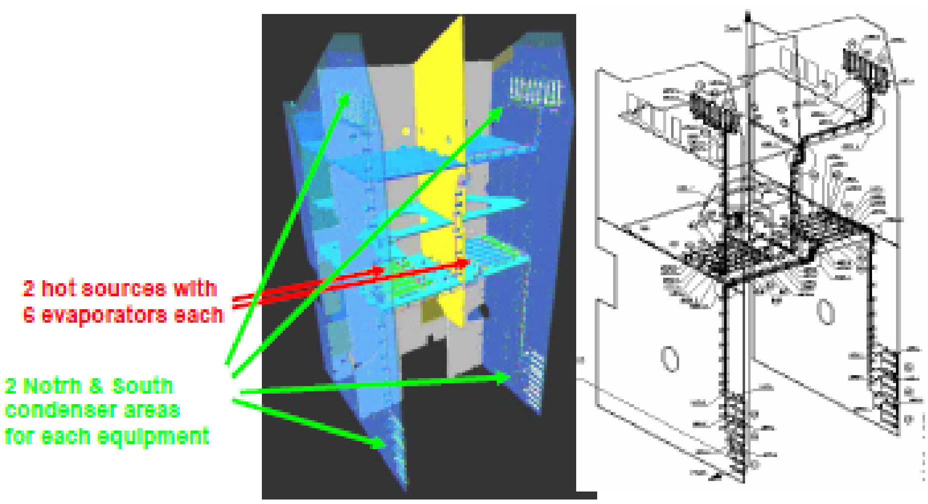
INMARSAT 4

- Use of 12 LHPs to cool 2 highly dissipative units

INMARSAT 4 LHP configuration



16

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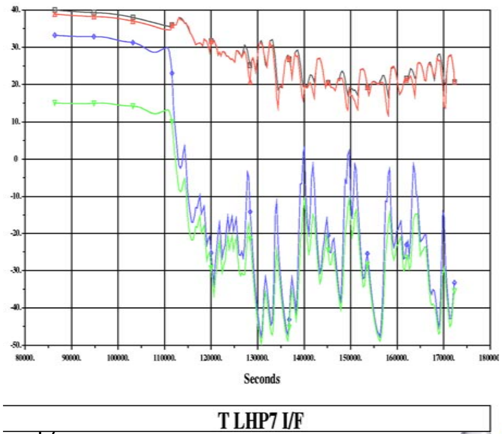
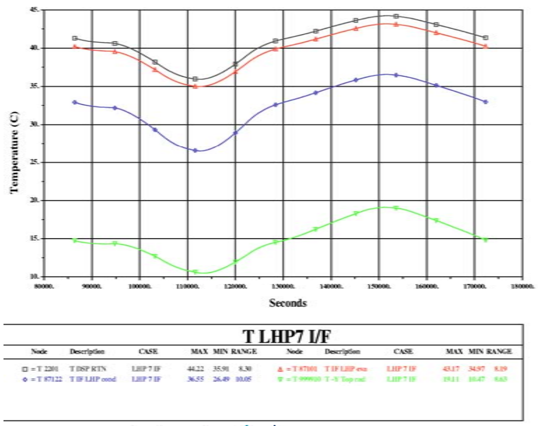
INMARSAT 4

- Interfacing LHP module with S/L model
  - Evaporator-condenser power tabulated conductances replaced by 12 LHP modules instances
  - Discrepancies to flight measures < 8°C
  - Time step reduction needed ⇒ Computation duration ≈x 10

Initial time step



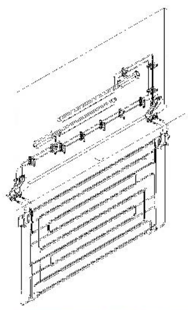
Reduced time step

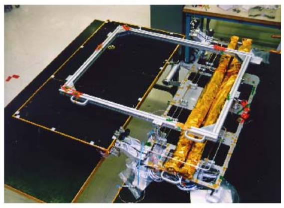


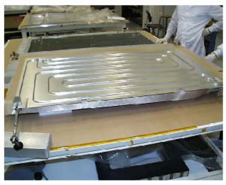
17

DELPHRAD

- **DEployable Lightweight High Performance RADiator EM**
  - **2 LHPs**
  - **Condenser embedded in radiator**
    - **3 // branches per condenser**
    - **Each condenser connected to one side of the radiator**
  - **Liquid lines:**
    - **3 parts: fixed on Spacecraft wall, flexible, fixed embedded in the radiator**
    - **Conductive & radiative exchanges**
  - **Vapor lines:**
    - **2 parts: fixed on Spacecraft wall, flexi**
    - **Conductive & radiative exchange with**



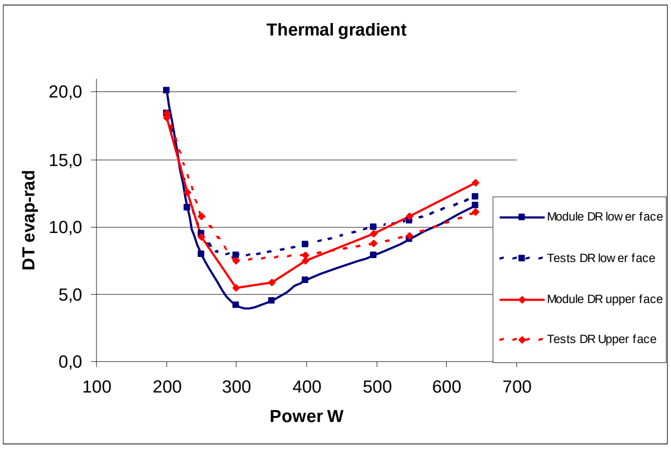




18

DELPHRAD

- Thermal gradient vs Power with stabilised results



Transition @ 300W observed for test and simulation results

- Good simulation of Start Up & Shut Down
  - temperature level
  - stabilisation duration

19

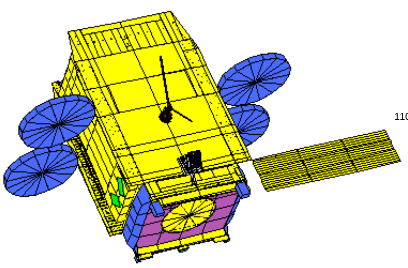
@BUS Prospective activity

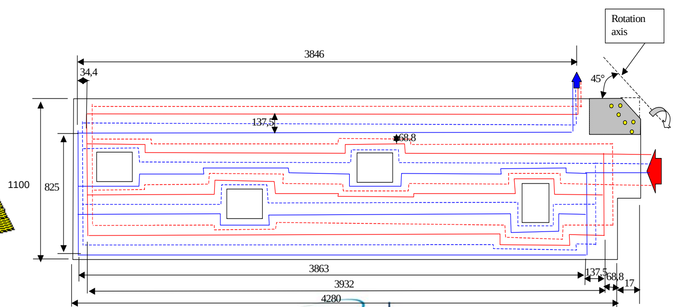
- DPR with 4 LHPs added to @BUS CDR model in order to:
  - **Validate the use of the LHP module in a large system model**
  - **Evaluate the impact in terms of CPU time**

⇒ **No evaluation of the thermal DPR performance**

⇒ **Power added to maintain the same temperature level on HP crossing**

-





@BUS conclusion

- LHP module can be coupled to Spacecraft system model (system simulations of EQ and SS performed with success)
- Overall time step had to be decreased from 50 s to 1 or 2s
  - ⇒CPU time multiplied by 24 (8 days wrt 8 hours) wrt @BUS model without LHPs

21

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22

Software availability

- Black box version
  - Confidential code put in object library, to be used as other user-defined libraries
  - Availability for last version v2.6.2
    - Thermica solver: OK, for version >= v4.3
    - Esatan : planned 01-2011 for new version delivered November 2010
- Available for free to the community
  - Black box version + Software User Manual + Installation manual
  - On-line support : organisation still to be defined (limited support during guarantee period)
  - Contacts:
    - Astrium: frederic.jouffroy@astrium.eads.net
    - TAS: anne.sophie.merino@thalesaleniaspace.com
    - CNES: Amaury.Laruedetournemine@cnes.fr

23

LHP MODULE : CONCLUSION

- Ability for European industry to use standard thermal software to predict thermal behaviour of space systems including LHPs
- Modular component approach

  → Creation of libraries of components for re-use
    - Evaporators
    - Fluids
    - condensers
- Validated through many test cases
- Computation time consuming:

  → Requires thermal solver performance improvement to deal with large models

  → Use of LHP module may be restricted to a few start/stop verification & sizing cases.
- Perspectives : New functionalities to be implemented (by-pass, Peltier, isolator, …)

24

APPENDIXES

25

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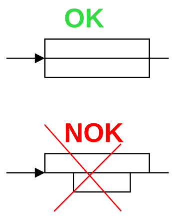
Lines modelling

- Tubing nodes (D type)
  - Vapour line:
    - up to 99 nodes & 5 sections to define flexible & rigid parts
  - Condenser
    - Up to 398 nodes
    - Up to 5 fully parallel branches

    Note: No intermediate topology applicable for computation



  - Liquid line
    - Up to199 nodes & 5 sections

  <u>Possible use of standard homogeneous tubing heating</u>

- Fluid nodes mapped to tubing nodes (B type)

26

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LHP definition: hardware components

- On file per LHP item
  - Evaporator (mini-LHP, LHP^2,…) *.EVAPHW
  - Vapour line (config specific) *.VAPLHW
  - Condenser (generic or specific) *.CONDHW
  - Liquid line (config specific) *.LIQLHW
  - Fluid (NH3,Water) *.PPTY
- *Example: condenser*
  - Number of branches
  - Length for each branch
  - Tubing
    - Hydraulic & thermal diameters
    - Linear conductance & capacitance

Files can be shared/reused for multiple LHP use & different applications (fluids, evaporators, condensers)

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Interface definition

- Couplings to be added in system model
  - Exemple GL(LHP1:101;20101)=xxxx;
  - Must be consistent with tubing meshing definition
- Evaporator I/F
  - To power source
  - Conductive & radiative heat leaks for body & reservoir
- Condenser I/F
  - To radiator
  - To heat sink (North-south HP for Telecom application)
- Liquid line
  - Radiative & conductive heat leaks (through attachement feet)
- Vapour line
  - Generally considered as adiabatic (only tubing-fluid exchanges taken into account)

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LHP Operation reporting in *.out* file:

- Input characteristics check
  - ⇒ All LHP definition data used (content of files) systematically output at start of run

```
****************************************************
 LHP MODULE version: 2.6.2
===== LHP SUBMODEL: LHP1                  INPUT PARAMETERS =====
|-----------------------------------------------------------
|                    LHP ASSEMBLY DEFINITION
|  DEFINED BY FILE :DELIV.LHP
|  Acceptance delivery case for LHP module
|-----------------------------------------------------------
|                    FLUID DEFINITION
|  DEFINED BY FILE : NH3.PPTY
|    Ammonia NH3 NIST reference
|-----------------------------------------------------------
|              EVAPORATOR HARDWARE DEFINITION
|  DEFINED BY FILE : DELIV.EVAPHW
|  LHP module acceptance case
| SADDLE CAPACITANCE (J/K)                  :        220.000
| BODY CAPACITANCE (J/K)                    :        100.000
| RESERVOIR BODY CAPACITANCE  (J/K)         :        200.000
| RESERVOIR VOLUME (m3)                     :      0.500E-03
|  ...
```

29

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Events reporting in *.out* file

- Numerical warnings
  - Table interpolation outside defined limits
  - Unconverged cyclic behaviour in steady-state
  - Pressure loss balance in condenser branches not reached (in case of laminar/turbulent transition)
  - Inconsistent heat flux transfer between tubing & fluid (due to sudden condition changes)
  - Etc….

30

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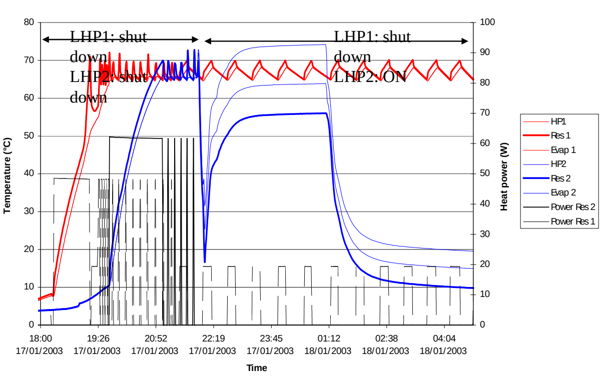
DELPHRAD

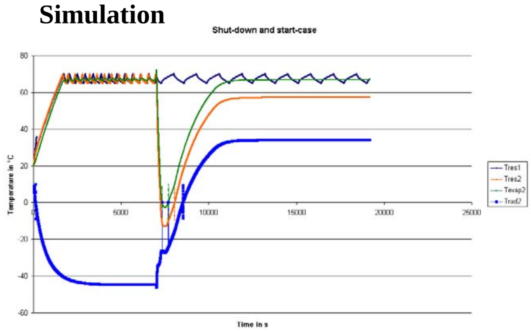
- Start up & Shut down simulation

Good simulation of SU & SD in term of temperature level & Stabilisation duration: **Test (73 min)/**

Simulation (67 min)



Simulation



		Start up	Shut Down
LHP1	Before 7000s After 7000s		50W on CC 20W on CC
LHP2	Before 7000s After 7000s	965W	50W on CC

31

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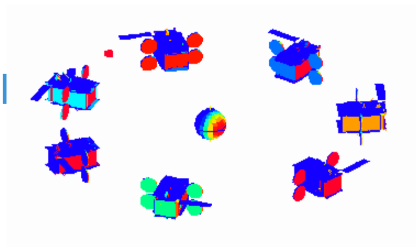
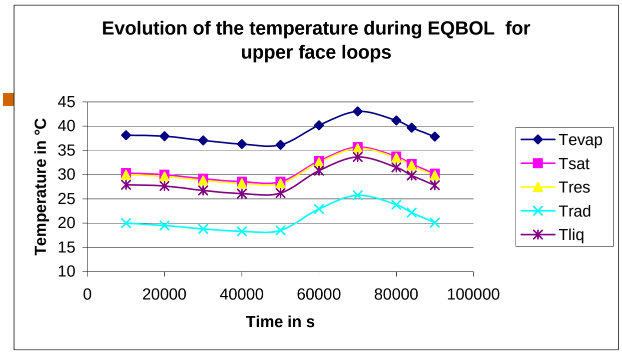
@BUS

- @BUS DPR Simulation –EQ BOL



T=0s



Power on LHP1= 779W
Power on LHP2= 781W
Power on LHP3= 773W
Power on LHP4= 772W

Additional Power rejected by DPR= 3100W (HR= 672W/m²)

32

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