Modeling Transient Operation of Loop Heat Pipes using Thermal Desktop™

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ABSTRACT

Loop heat pipes (LHPs) are used in multiple terrestrial and space applications. Transient analysis of conventional and advanced loop heat pipes with complex radiators under varying conditions where the heat load and the effective sink temperature change in time can be best accomplished using Thermal Desktop™.

This paper presents a transient model of a LHP developed using Thermal Desktop™ (Sinda/Fluint). It includes the evaporator connected to the reservoir and condenser with fluid transport lines with bends, flow balancers, and connectors. The condenser is bonded to a honeycomb panel with two face-sheets spreading thermal energy across the radiating surfaces. The model was correlated to the thermal-vacuum test data.

The modeling provided better understanding of the critical transient fluid-flow mechanisms encountered in the LHP under transient operational conditions. Analysis of the numerical results shows that the secondary wick should be transporting liquid from the reservoir to the primary wick during transient operation where the sink temperature is decreasing or the evaporator heat load is being reduced.

LHP typical configuration and operation

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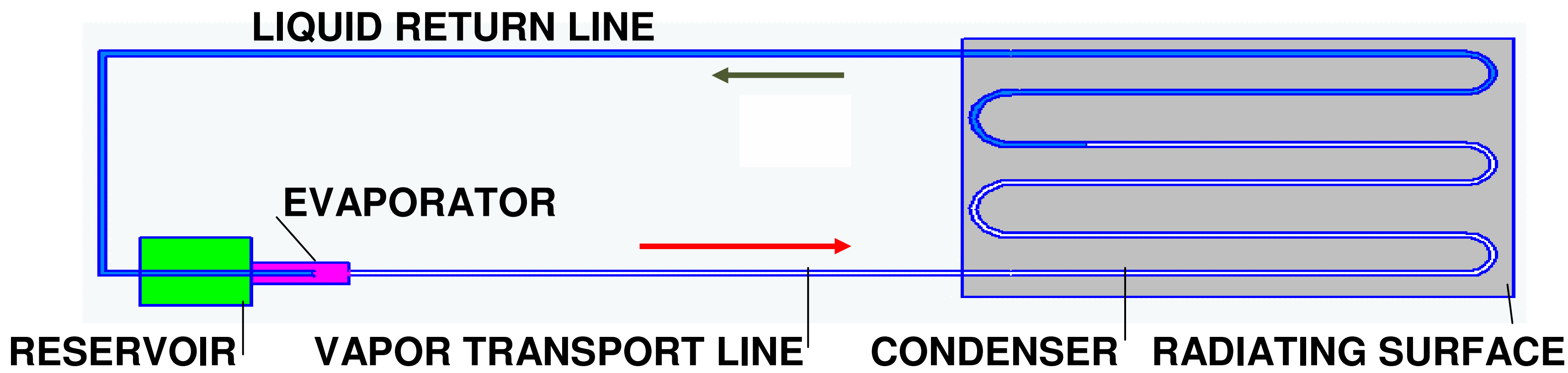
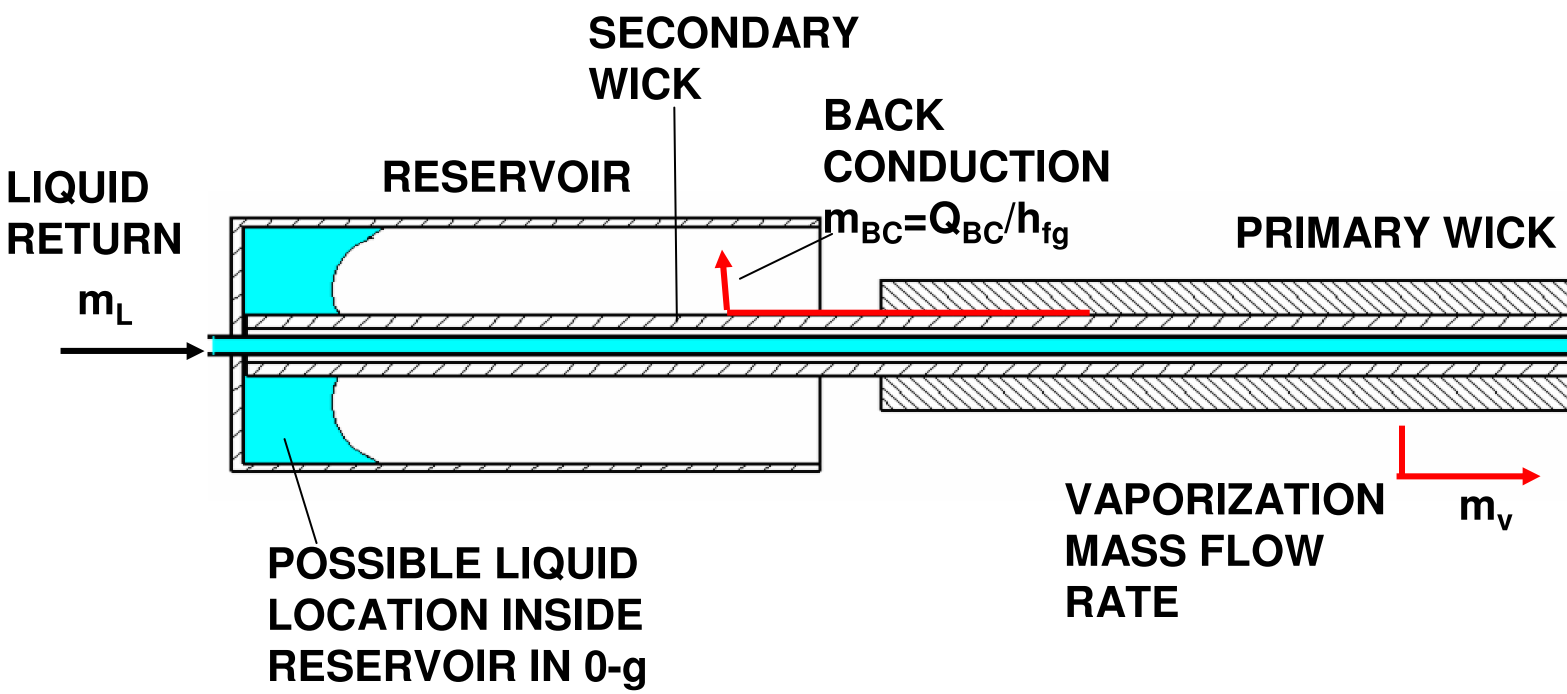




MODELING INTENT AND IDEOLOGY

The secondary wick requirements result mainly from the fluid accumulation in the condenser affected by the decreasing heat sink temperature and/or decreasing heat load (rate of vaporization). Secondary wick design/geometry is not needed to calculate the secondary wick requirements.

The condenser/radiator is the component with the highest mass and surface area. The rate of the working fluid accumulation in the condenser depends on several factors and processes such as:

- Sink temperature variation
- Heat load (vaporization rate) variation
- Variation of the absolute temperatures and pressures
- Variation of the fluid thermophysical properties
- Conduction in the face sheets
- Back conduction
- Vapor breaking through the condenser into the reservoir
- Variation of the liquid subcooling coming to the reservoir due to the fluid accumulation and changes in the radiator temperature
- Parasitic heat inputs to the reservoir and liquid return line through radiation
- etc.

The LHP response to a cyclic heat input and environment precisely repeats itself after several cycles, essentially not depending on the initial conditions for the first cycle.

Details of the Transient Reservoir Energy Balance

$$\underbrace{\left(M_R c_{pR} + M_{RL} c_{pL}\right)\frac{dT_R}{d\tau}}_{\text{Sensible heat resulting from reservoir temperature change}} = \underbrace{C_{BC}\Delta P / \frac{dP}{dT}}_{\text{Back conduction}} + \underbrace{m_{v,o}\left[h_{fg} + c_{pv}(T_v - T_R)\right]}_{\text{Vapor returning from condenser and condensing in reservoir (only for fully open condenser)}} -$$

$$\underbrace{m_L c_{pL}(T_R - T_L)}_{\text{Liquid subcooling}} + \underbrace{\frac{\Delta M_{L,R}}{\Delta t} h_{fg} \frac{\rho_v}{\rho_L - \rho_v}}_{\text{Energy term related to vapor/liquid displacement in the reservoir}} + \underbrace{\frac{\sigma A_R (T_{se}^4 - T_R^4)}{\frac{1}{\varepsilon_R} + \frac{1}{\varepsilon_{se}} - 1}}_{\text{Radiation parasitics}} \qquad (1)$$

Liquid subcooling is assumed to be consumed by the Reservoir

This equation is presented for communication purposes only, while it has a different form and might have additional terms in Sinda/Fluint model

Liquid Mass Flow Rate in the Secondary Wick

The main function of the 2ry wick is to compensate for the mass flow rate imbalance at the primary wick during fluid transients, by drawing additional liquid from the reservoir to the primary wick.

The fluid mass flow rate out of the primary wick is due to the (a) vapor generated at the wick/wall interface flowing into the vapor transport line, m_V(kg/s), and (b) vapor going into the evaporator core due to the "back conduction" Q_{BC}/h_{fg} where Q_{BC} is the "back conducted energy" and h_{fg} is the latent heat of vaporization. The liquid is returning to the primary wick through the bayonet with a variable mass flow rate of m_L (kg/s), bringing the subcooling to the reservoir, which can be approximated as $m_L c_{pL}(T_{res}-T_{liq})$.

Note that the liquid can flow to the reservoir together with vapor if the condenser is "vapor-open" (L_v = 100%, X≥0).

As soon as the radiator temperature is below the vapor temperature, there is always some liquid return to the reservoir, even if the condenser is "vapor-open" (unless the flow in the liquid return line stagnates.)

Definition of the Secondary Wick Requirement

Based on the mass balance around the primary wick control volume:

$$m_{SW} = m_V - m_L + Q_{BC}/h_{fg}, \text{ where}$$

$$(m_V - m_L) = dM_{fluid\_cond}/dt + (m_V - dM_{fluid\_cond}/dt)X_{out}$$

is the result of accumulation of the fluid in the condenser and non-zero quality of the flow at the condenser outlet X_{out}. Multiplying by h_{fg} (latent heat of vaporization) and rearranging,

$$\boxed{Q_{SW} = dM_{fluid\_cond}/dt\ h_{fg} + Q_{BC} + (m_V - dM_{fluid\_cond}/dt)X_{out}\ h_{fg} \quad (1)}$$

we derive the "secondary wick transport requirement, Q_{sw}". There are three components in Qsw due to (a) fluid accumulation in the condenser, (b) vaporization related to the back conduction, and (c) vapor breaking through the condenser into the reservoir

Note that Qsw is an output of the transient model in terms of power for the convenience of comparing to secondary wick capability. Qsw does not represent heat flow between the reservoir and evaporator, i.e., Qsw does not appear in the model energy balance for the evaporator and reservoir control volumes.

Description of the TD™Transient LHP Model

The Sinda/Fluint model simultaneously solves the flow momentum, energy, and mass conservation equations for the two-phase fluid flow. It includes all three heat transfer mechanisms: convective, conductive, and radiative, as well as accounts for the phase change heat transfer. The pressure drops and heat transfer for the homogenous two-phase flow are automatically calculated by the solver using the established correlations based on the local conditions.

There are more than 250 fluid lumps (and also 250 corresponding nodes) in the model in order to represent the condenser line and the transport lines in sufficient detail.

There are 400 nodes with corresponding surface areas representing the radiator and radiating to the heat sinks.

The reservoir is represented as a tank with a given volume linked to the vapor space in the evaporator across the primary wick via CAPPMP and IFACE macros.

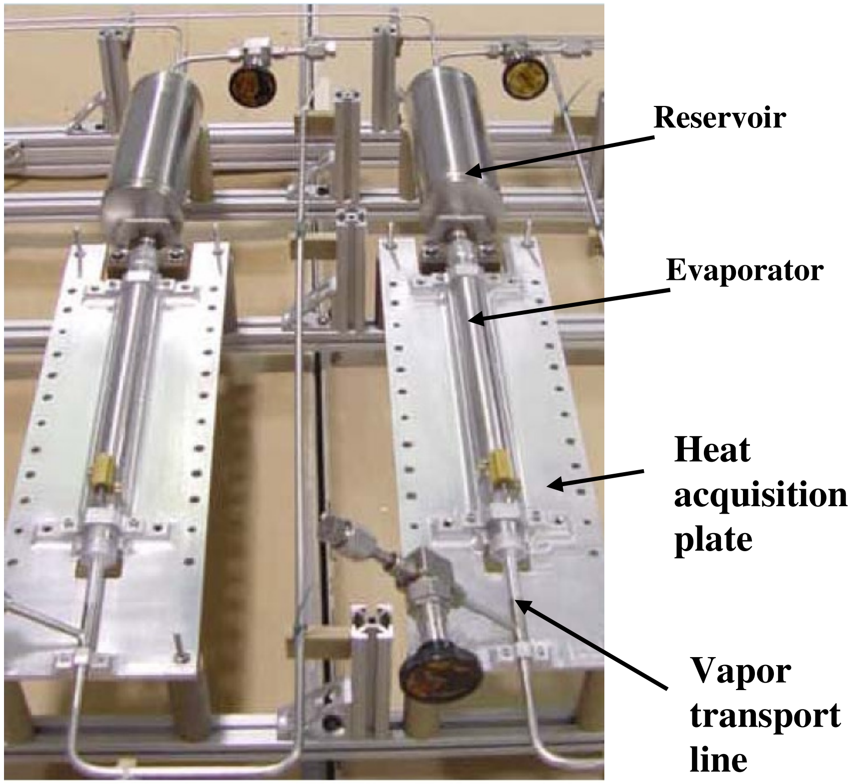
The fluid mass in the reservoir (as well as in the condenser) varies in time.

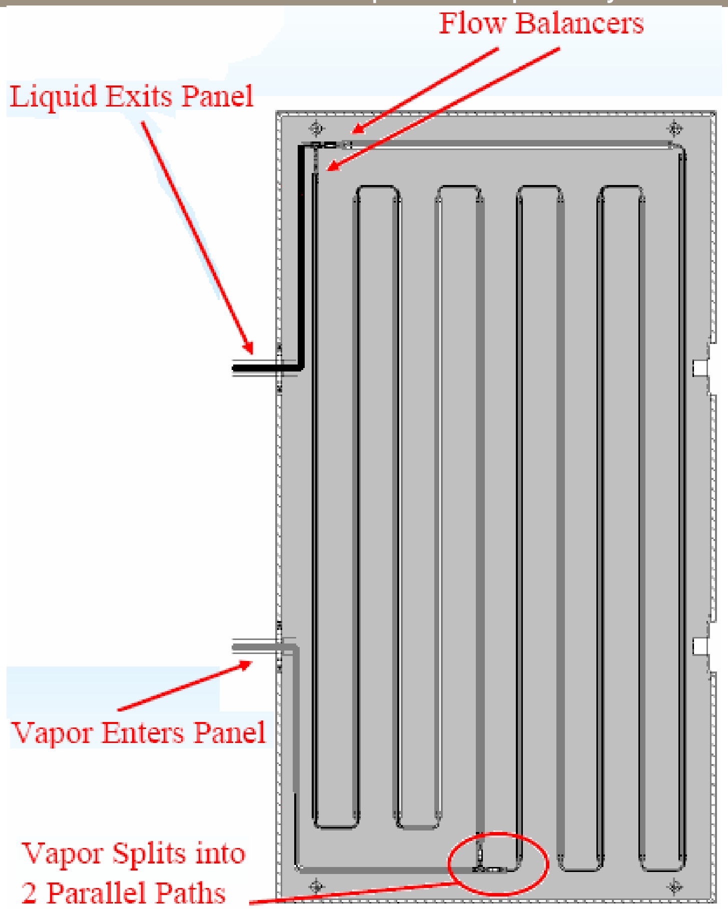
The evaporator heat load and temperatures of the two heat sinks vary in time.

The reservoir wall and evaporator wall have specified surface areas radiating to the corresponding (“top”) heat sink.

The flow quality for each lump is calculated by Sinda/Fluint based on the pressures, temperatures, and lump energy balance.

Components of the modeled LHP





Two parallel condensers

TOP VIEW OF THE MODEL

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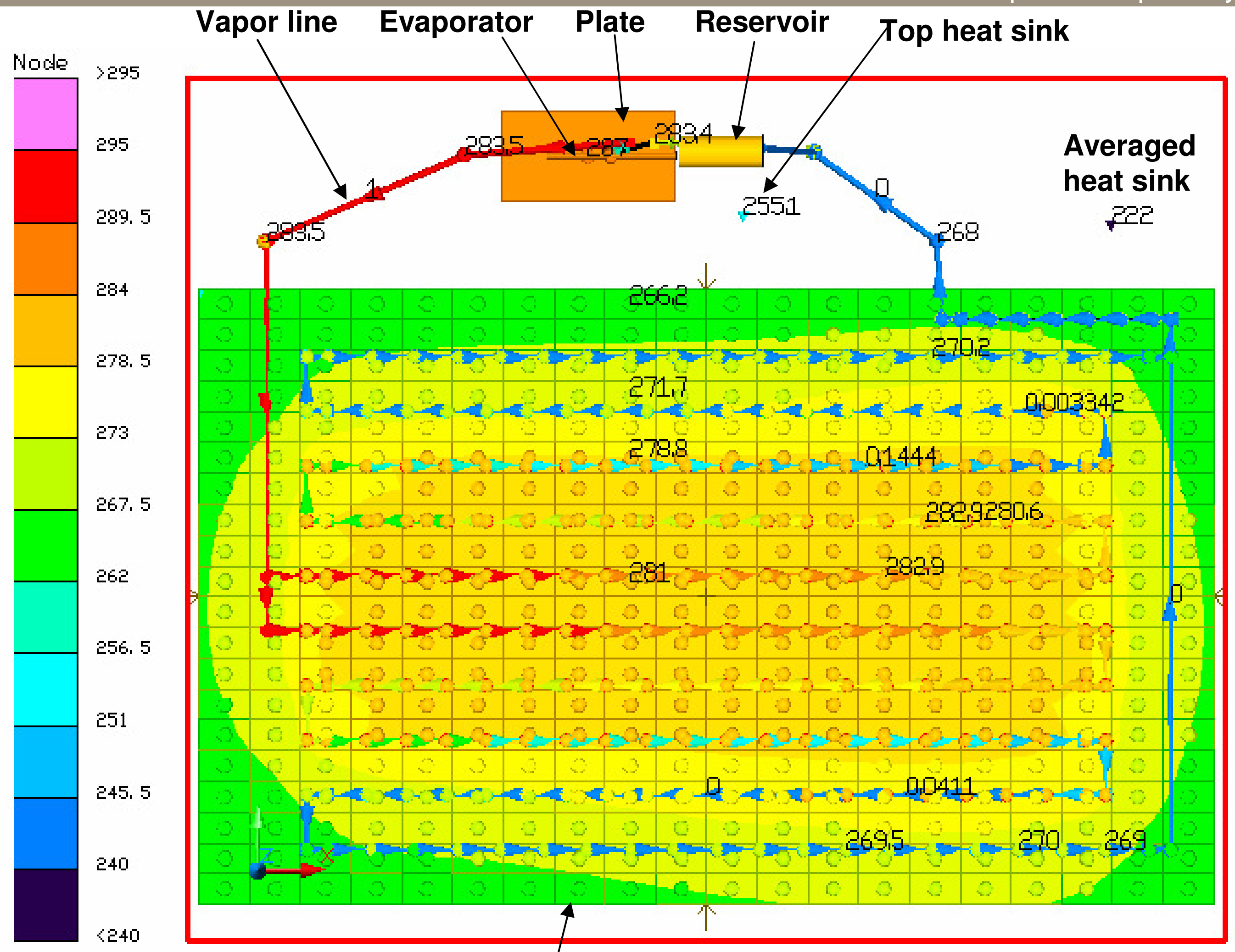
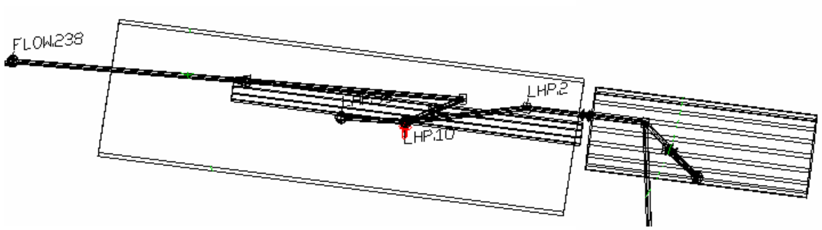
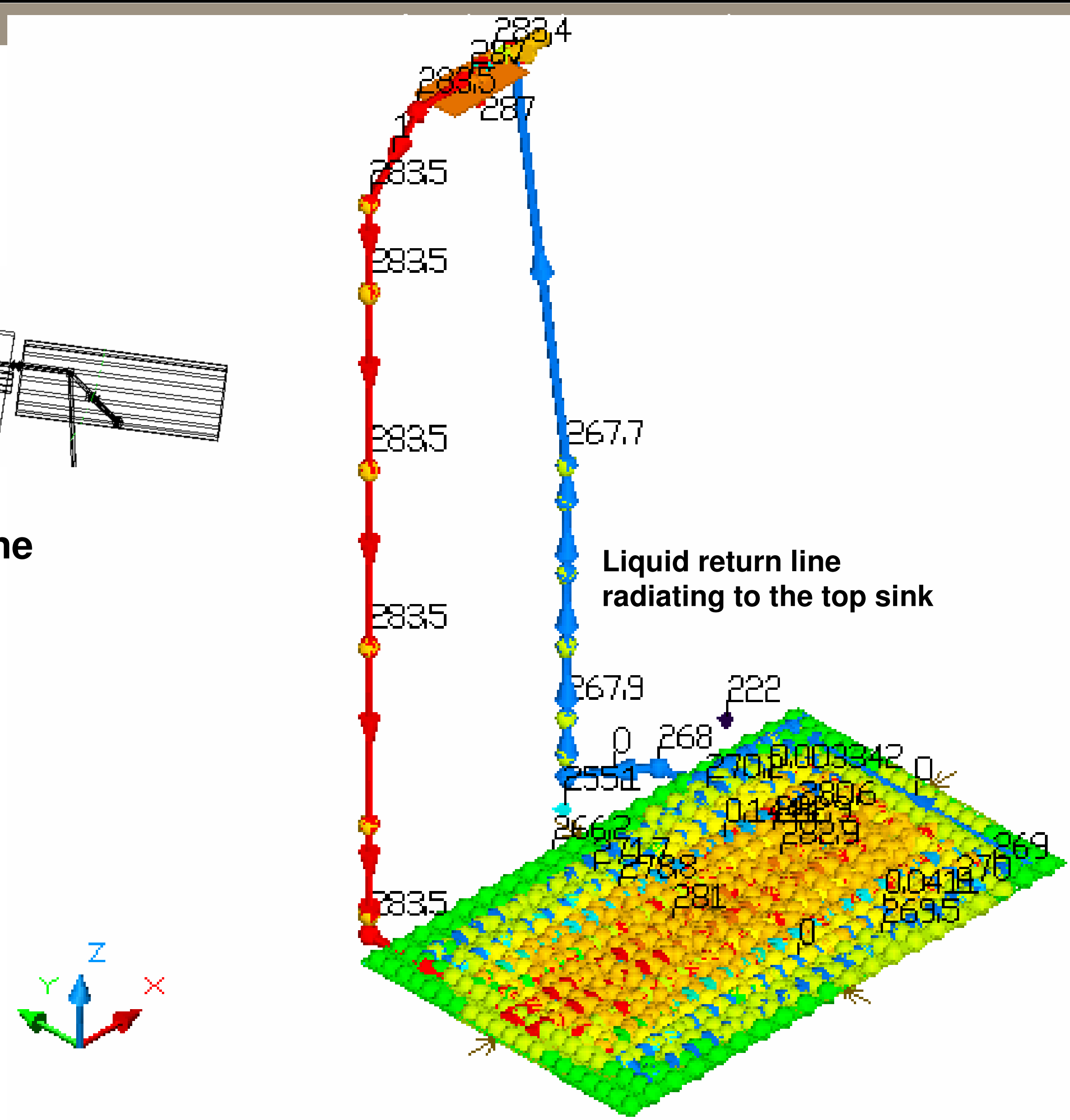


Radiator plate with condenser lines (radiates to the averaged heat sink)

ISOMETRIC VIEW OF THE MODEL



Evaporator model using one CAPPMP



Liquid return line radiating to the top sink

Transients during the 400-200-500 W power steps

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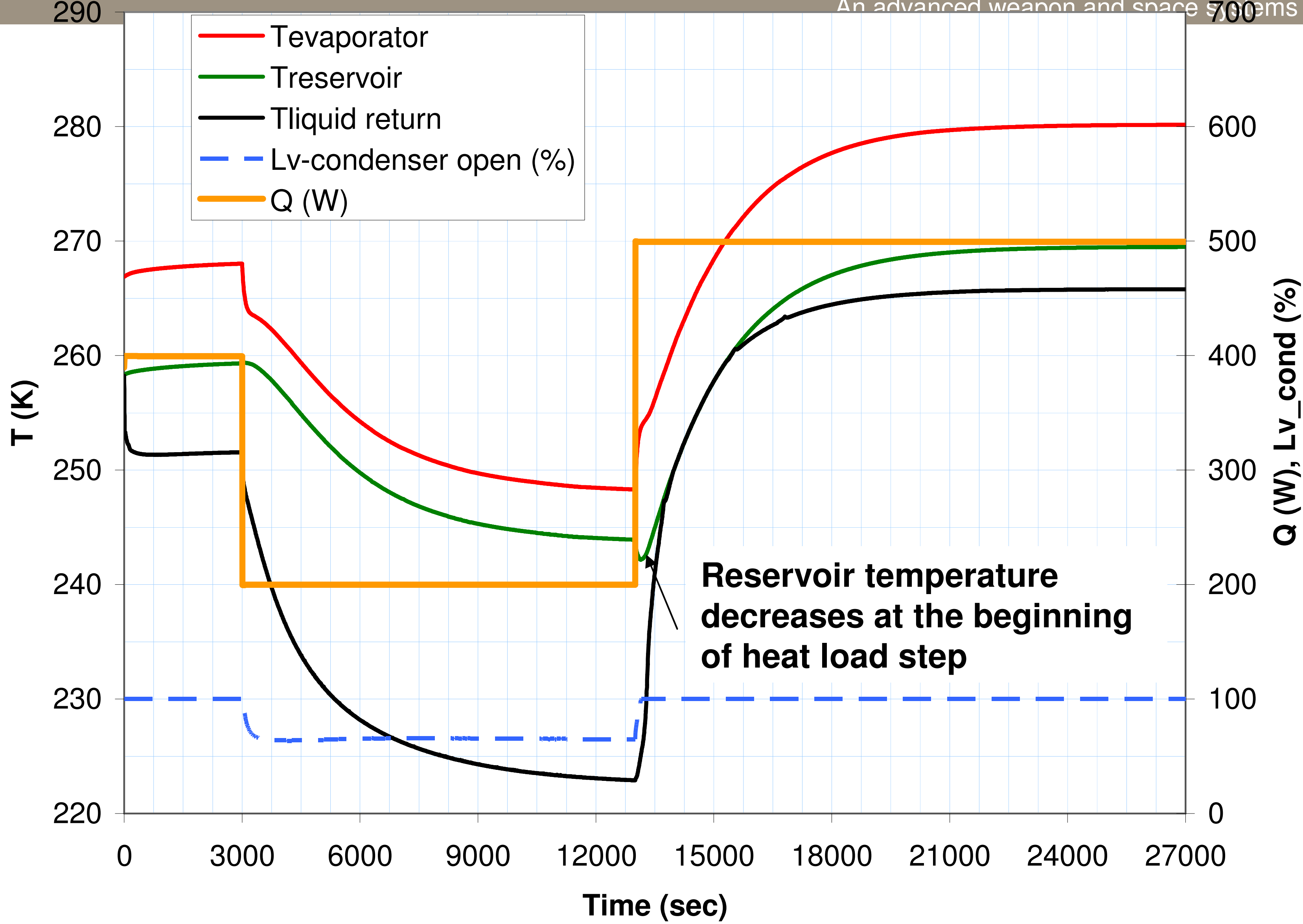
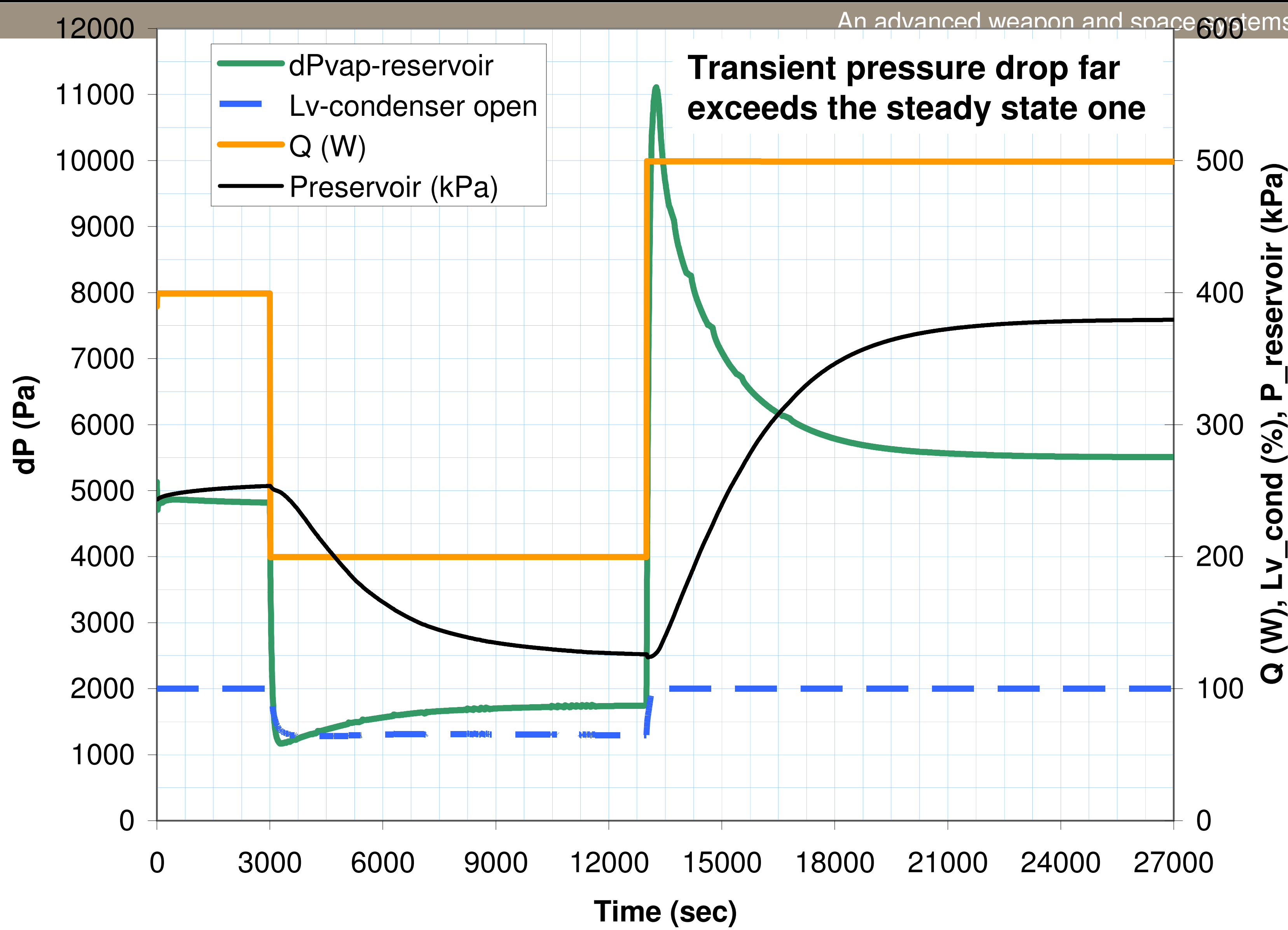


Pressure transients during the power steps



Transient LHP Model Correlation/Validation

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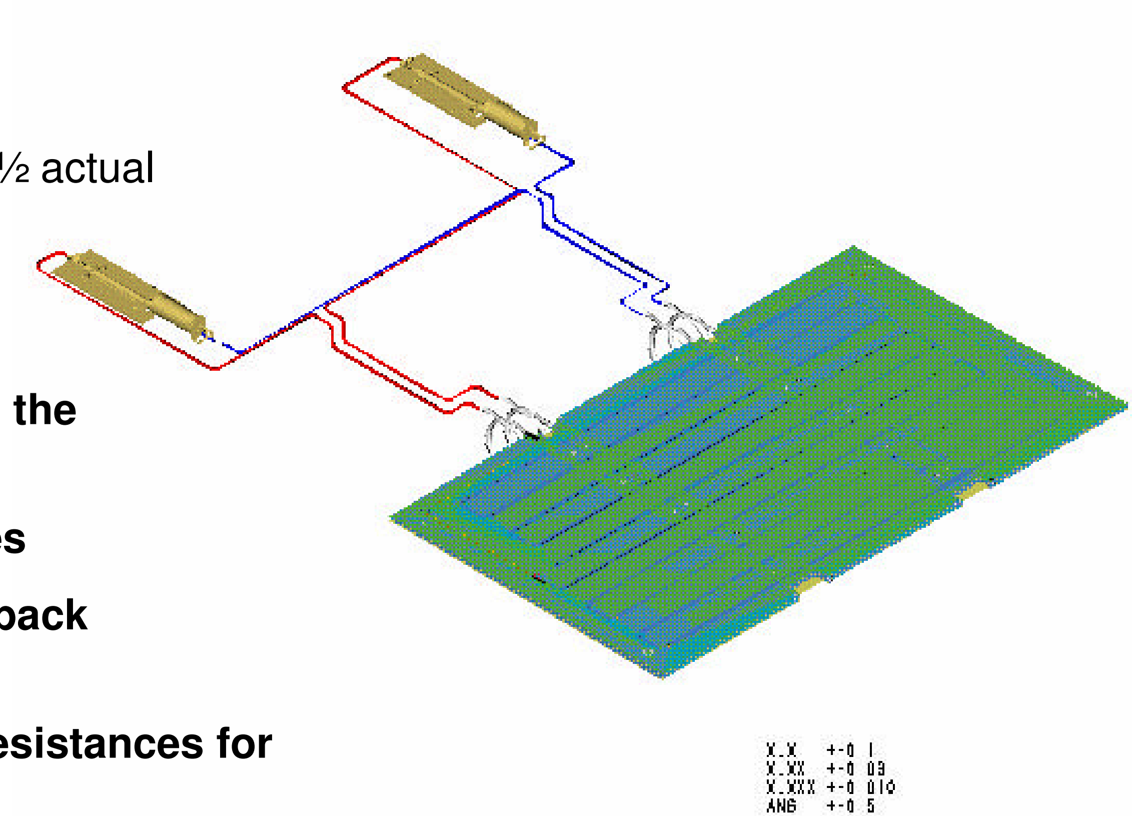
Thermal-Vacuum test data provided by the customer were used to correlate/validate the transient LHP model

Only 1 LHP modeled

- Condenser mass for model = ½ actual condenser mass



Parameters considered during the correlation effort

- **Adjusting surface emissivities**
- **Selecting correlation for the back conduction**
- **Introducing local hydraulic resistances for the two flow balancers**

Correlation to the Thermal-Vacuum Test Data

The effective emissivity of the radiator surface was adjusted for the thermal-vacuum testing (lower than for the flight unit predictions).

The back conduction between the evaporator and reservoir was adjusted from the classical level to better match the temperature of the liquid return line measured during the thermal-vacuum tests.

The reservoir and evaporator temperatures used in the model are mass-averaged, while in the test data these temperatures are calculated using outputs of several thermocouples. This might account for some difference between the predictions and measurements.

Comparison/correlation with the TV test data for LHP A-2

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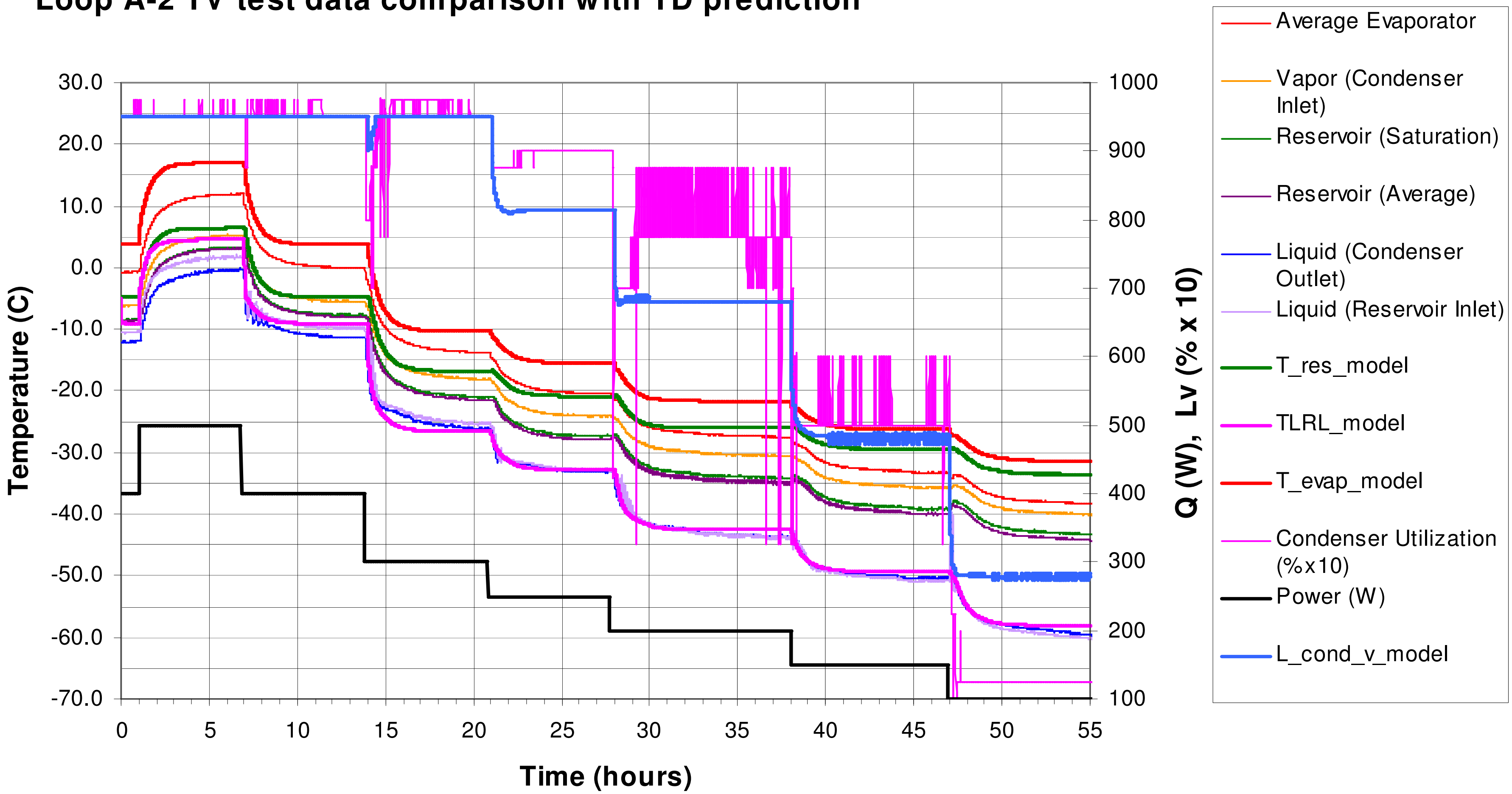
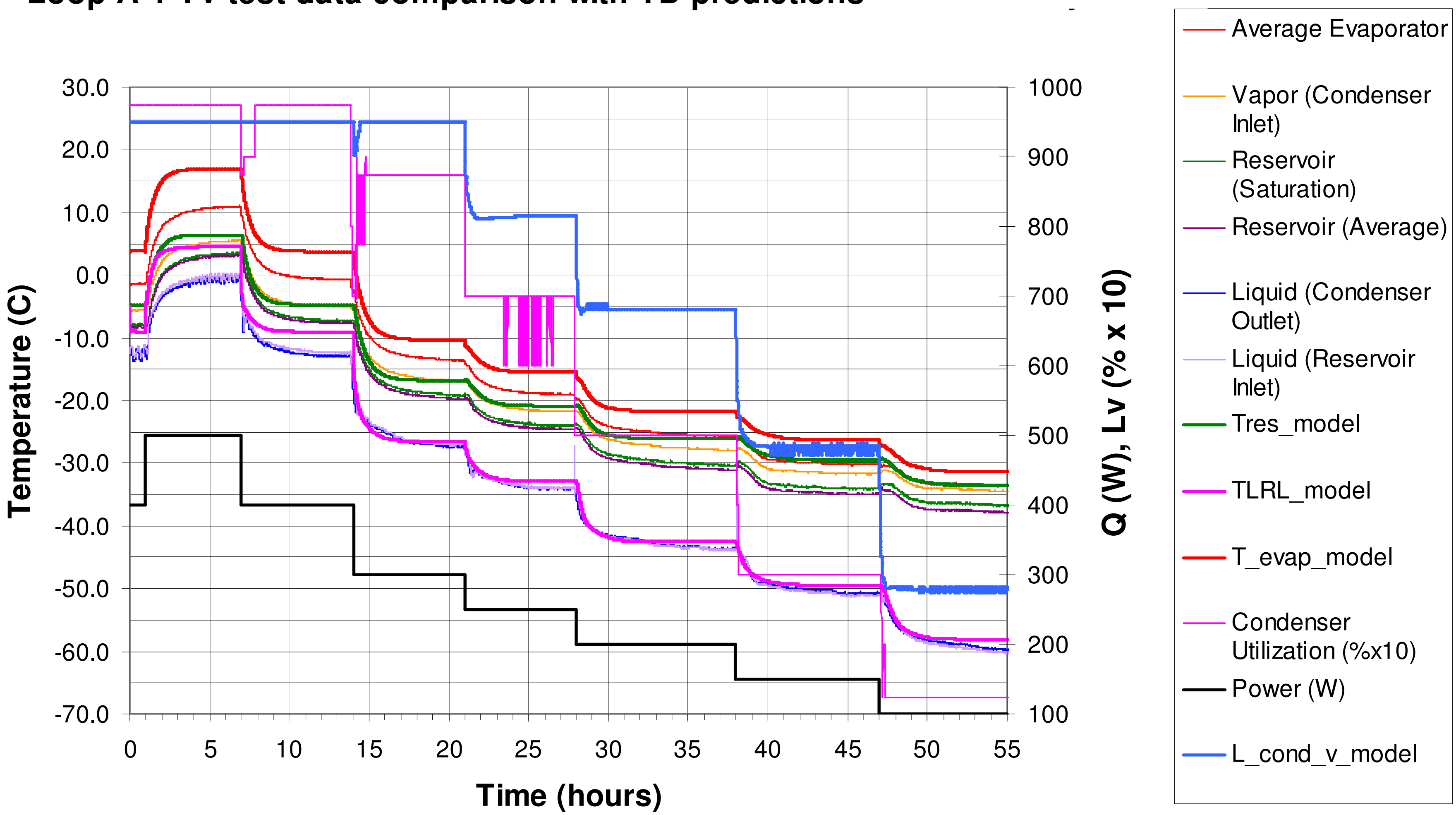
Loop A-2 TV test data comparison with TD prediction



Predicted TLRL and L_v match the test data reasonably well

Comparison/correlation with the TV test data for LHP A-1

Loop A-1 TV test data comparison with TD predictions



The predicted vapor-open condenser length better matches data for LHP A-2. The measurements were done with the accuracy of 20%. The two LHPs have different Lv.

Secondary wick requirements of 200 W during the power steps

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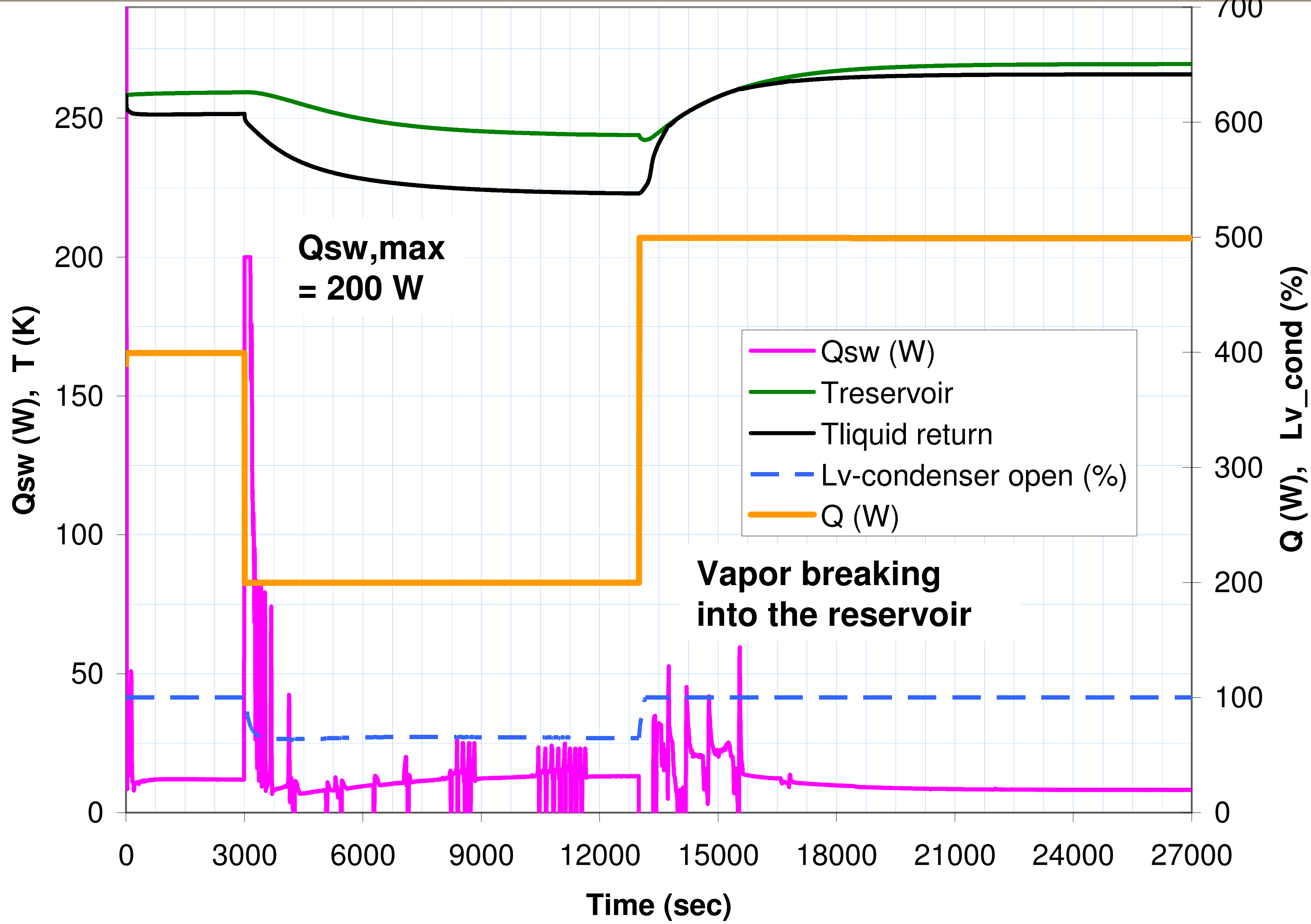

Secondary Wick Requirements during gradual decrease of the heat load and heat sink temperature

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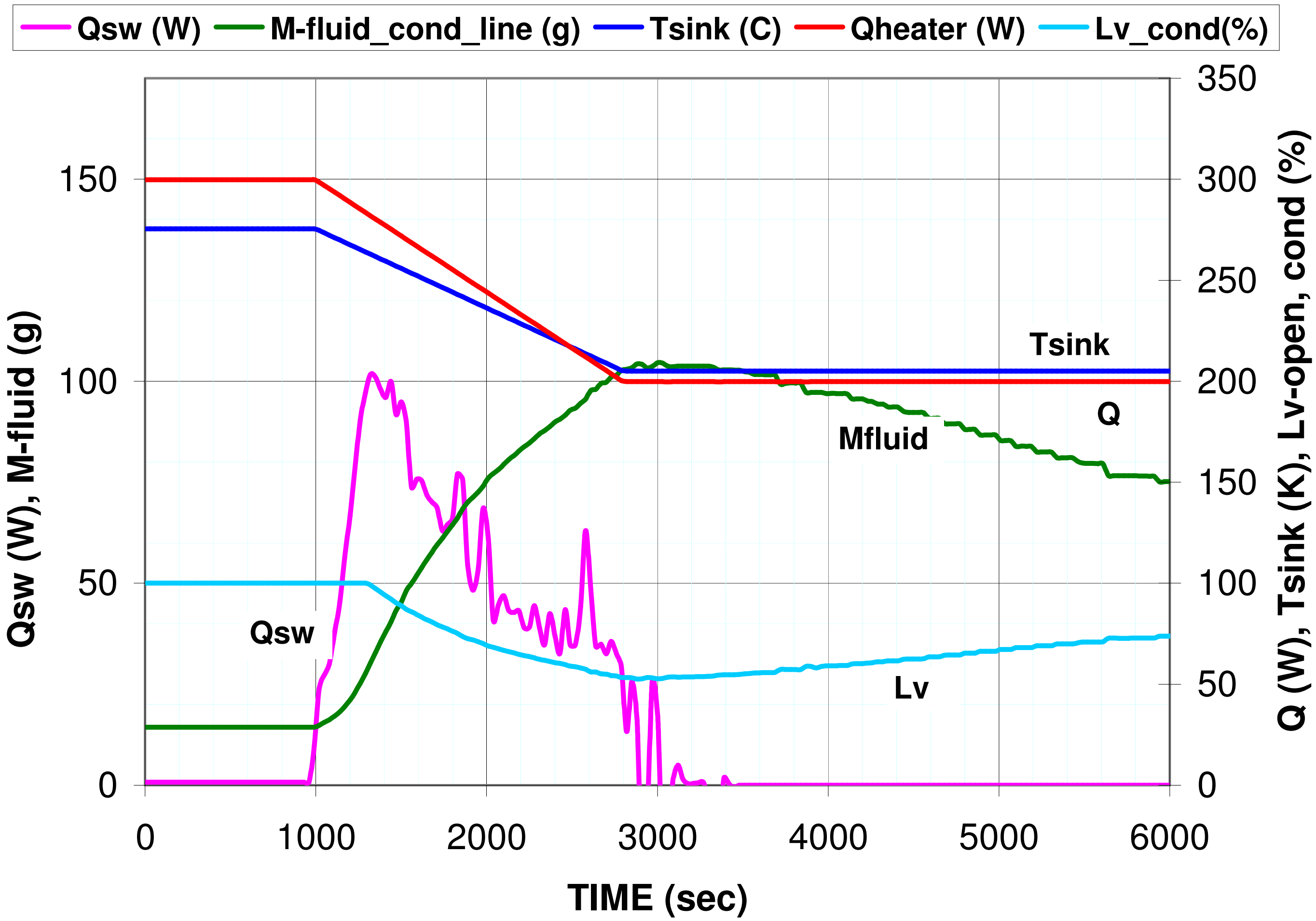

The secondary wick should transport liquid with the mass flow rate equivalent of 100 W for this particular transient case.

SUMMARY

- Thermal Desktop™ transient LHP model was correlated to the thermal-vacuum test data

- The secondary wick requirements can be rather high during transient situations where the heat load and/or the heat sink temperature are decreasing

- Transient modeling of a conventional LHP is needed to account for the transient phenomena at the design stage, such as the pressure drops during the power cycling, higher rate of vaporization due to an attached thermal mass, etc.

- Transient modeling is necessary for temperature control systems using LHPs