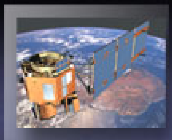

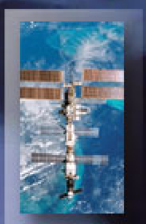

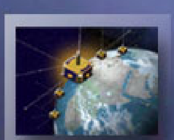

Modeling Two-Phase Loops with Several Capillary Evaporators

Dmitry Khrustalev, Kimberly Wrenn, and Dave Wolf

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Modeling Two-Phase Loops with Several Capillary Evaporators

SWALES AEROSPACE

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ABSTRACT

Two-phase loops with several capillary evaporators are being developed for a variety of existing and future space applications. While modeling of loop heat pipes with one or two conventional evaporators is relatively straightforward and can be done, for example, using Excel VBA, modeling of loops with several three-port or four-port evaporators requires more specialized software such as Thermal Desktop™.

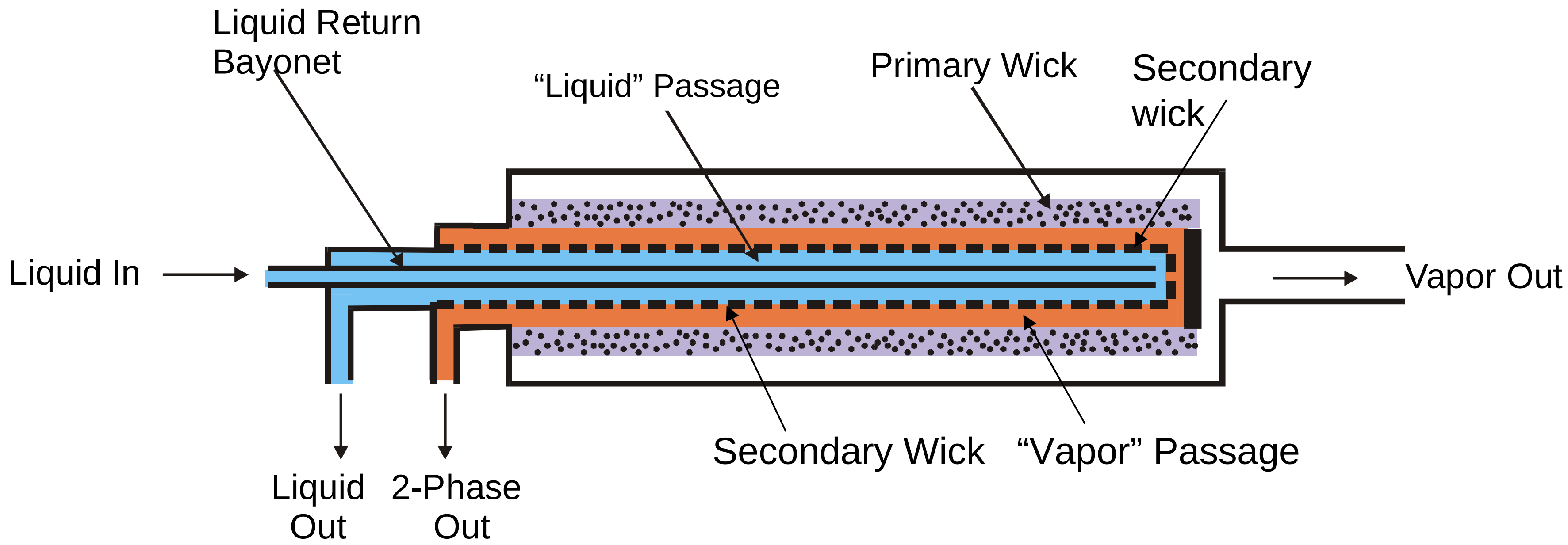
This paper presents steady state Thermal Desktop™ (Sinda/Fluint) models for systems with three main and one secondary capillary evaporator. The main evaporators have four ports and are interconnected with multiple fluid lines with bends, valves, and connectors. The system components also includes a temperature-controlled two-phase reservoir, condenser, back-pressure regulator, local heat exchangers, etc.

The modeling provided better understanding of the critical fluid-flow mechanisms encountered in the experimental two-phase system. While there are several ways to interconnect the four-port evaporators together, modeling also helped to select more reliable configurations capable of operating with the main evaporators located on different elevation levels and with non-uniform heat load distribution.

Various Thermal Systems to Cool Multiple Heat Sources

- **Pumped Single Phase**
  - Single phase liquid circulated by mechanical pump
  - Heat acquired through microchannel heat exchangers
  - Heat rejected to heat pipe radiator
- **Two-Phase Capillary System with Several Evaporators ("passive") is the focus of this presentation**
  - Capillary wicks in evaporators sustain pressure drops in the system
  - Secondary flow loop is supported by secondary LHP evaporator
  - Heat rejected through direct condensation radiator
- **Capillary Hybrid System**
  - Capillary wicks in evaporators sustain pressure drops in the vapor lines
  - Secondary flow loop is supported by mechanical pump
  - Heat rejected through direct condensation radiator
- **Pumped Two Phase System**
  - Two phase flow is circulated by mechanical pump
  - Heat acquired through heat exchangers
  - Heat rejected through direct condensation radiator
- **Spray Cooling**
  - Two phase flow and spray cooling nozzles are supported by mechanical pump
  - Heat acquired through spray cooling nozzles
  - Heat rejected through direct condensation radiator

Schematic of Capillary Evaporator with Four Fluid Ports



Advanced capillary evaporators have 4 fluid ports:

(1) liquid supply,

(2) outlet of the vapor generated in evaporator,

(3) "sweepage" outlet for the fluid inside the secondary wick (liquid), and

(4) "sweepage" outlet for the fluid outside the secondary wick (vapor)

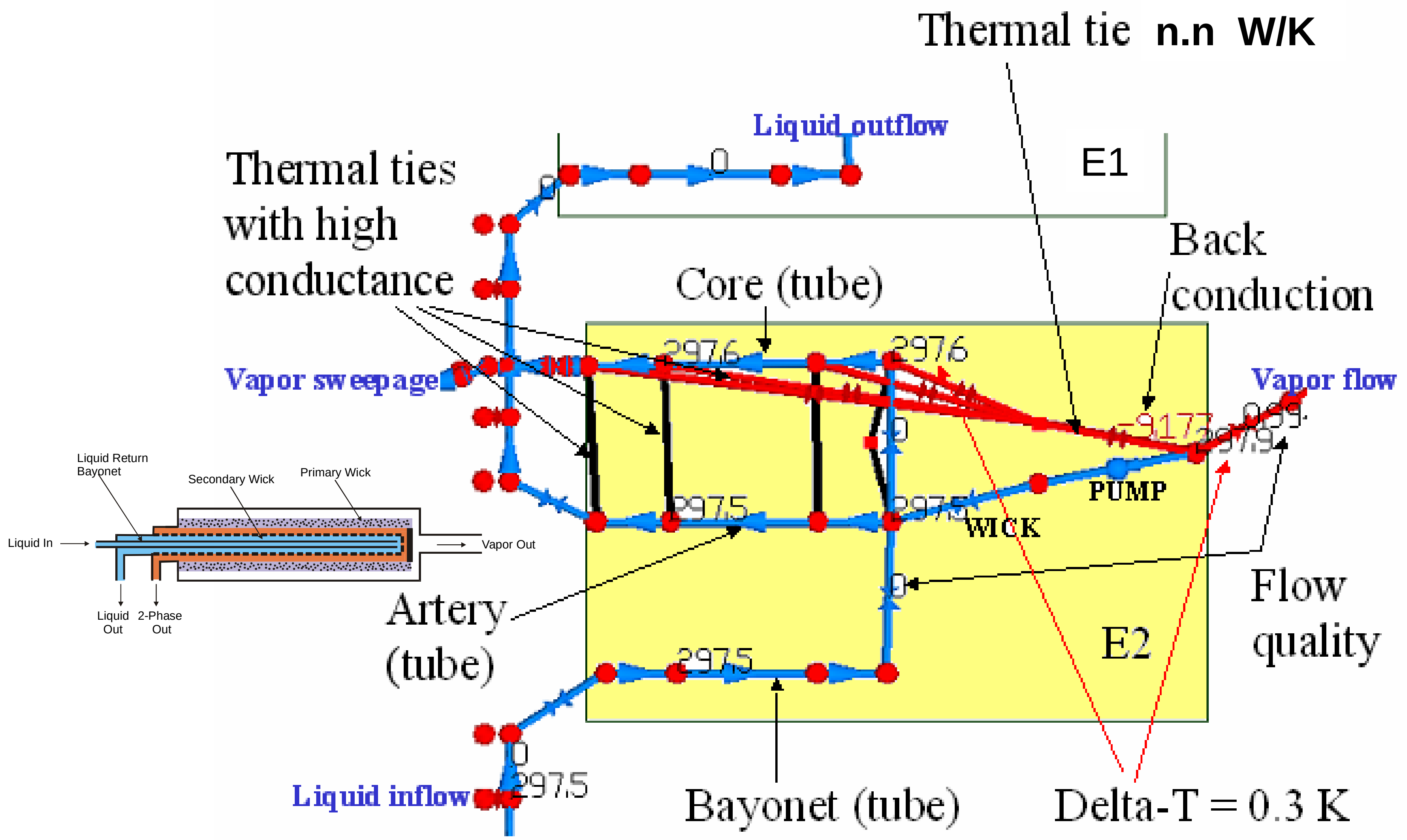
Note that the liquid supply mass flow rate exceeds that of the vapor generated by the primary wick. Thus evaporators can be connected in series as well as in parallel

Comments on two models of the evaporators

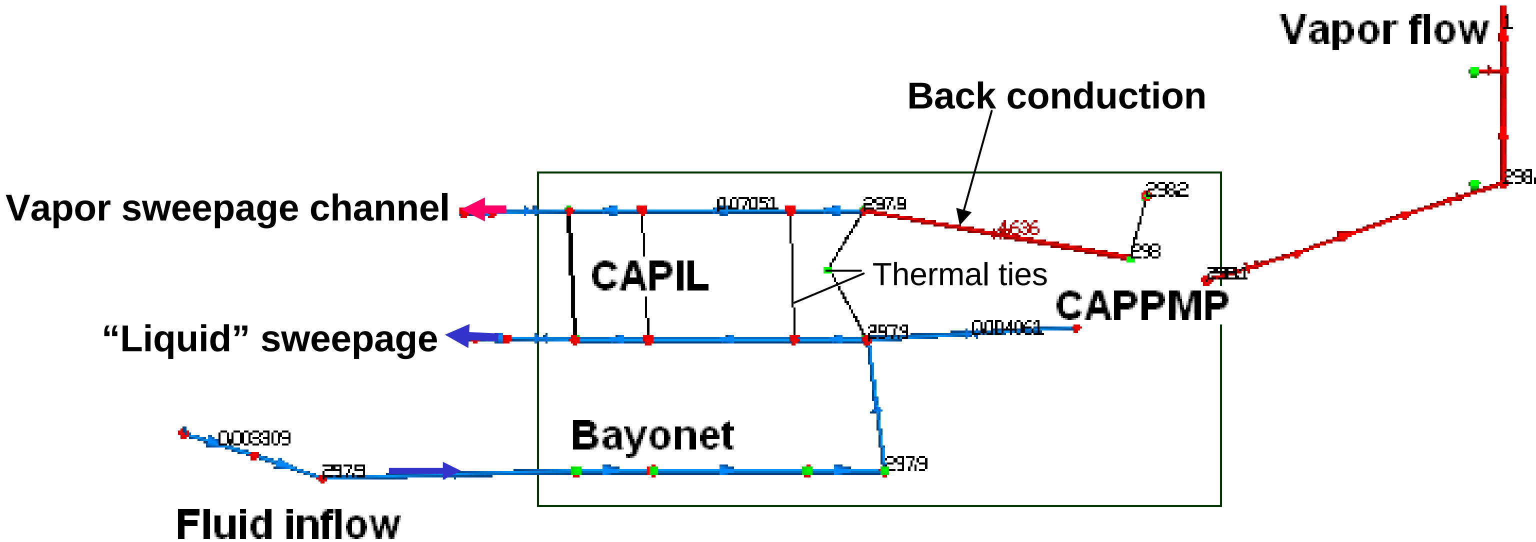
- **Evaporators modeled as constant mass flow rate pumps ("set flow") in early model development while they fully represent such features as:**
  - Pressure drops needed to move the fluid through transport lines
  - Pure vapor generated at the evaporator outlet (heat load matches the mass flow rate)
  - Back conduction specified based on the wick conductance

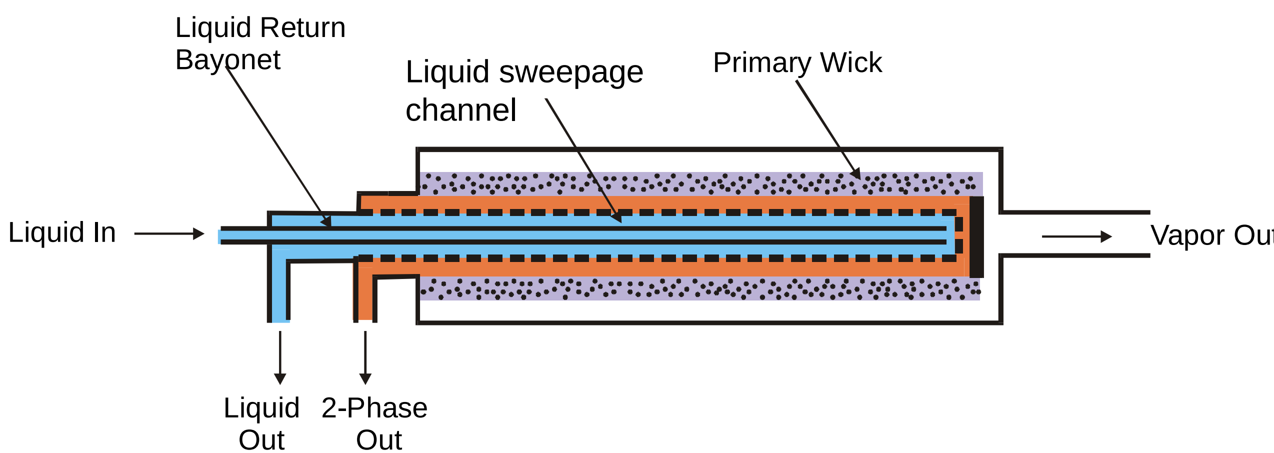
- **More accurate evaporator model includes CAPPMP function used for primary wicks and CAPIL for secondary wicks to better describe cases with**
  - Pressure difference between liquid and vapor passages inside evaporator core
  - Pressure difference across the primary wick affected by mass forces or fluid transients

Detail View of the evaporator (4 ports) model using "Set Flow" connector (pump)

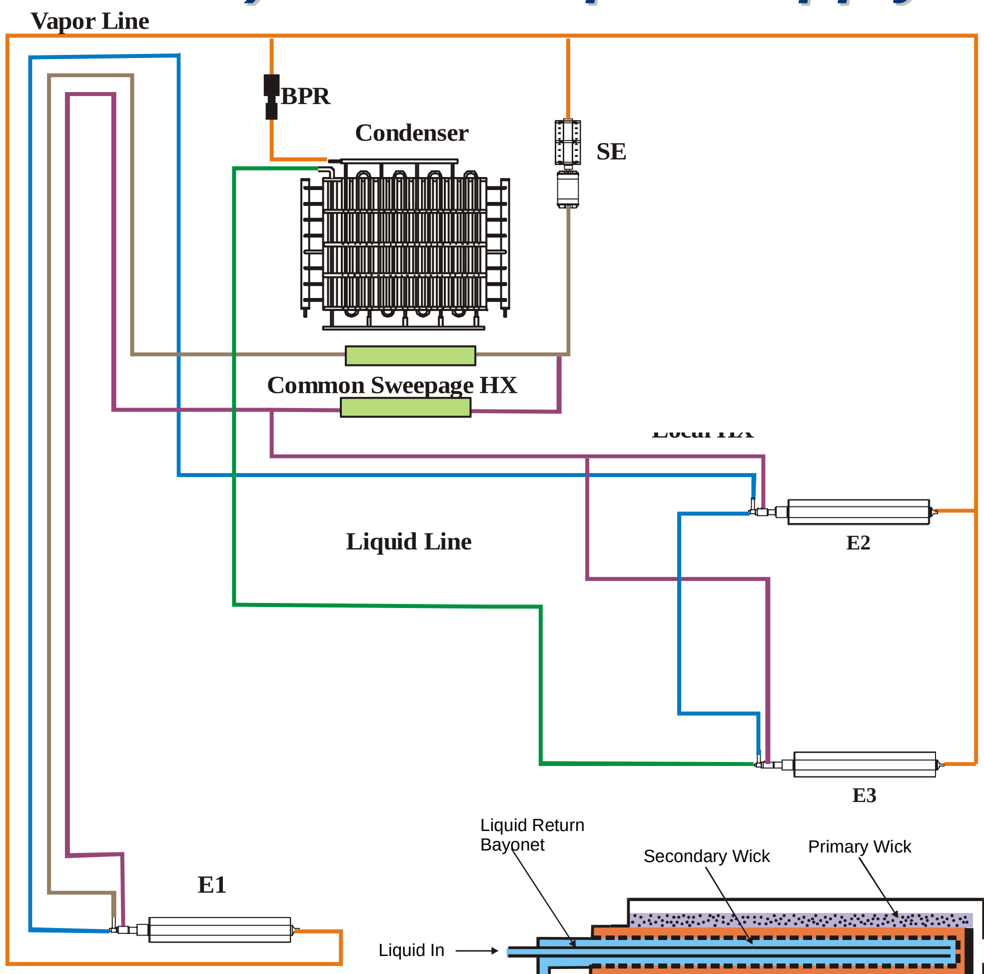


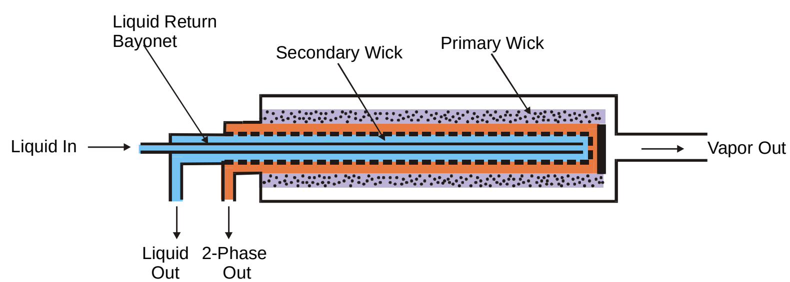
Detail View of the evaporator (4 ports) model using CAPPMP and CAPIL connectors



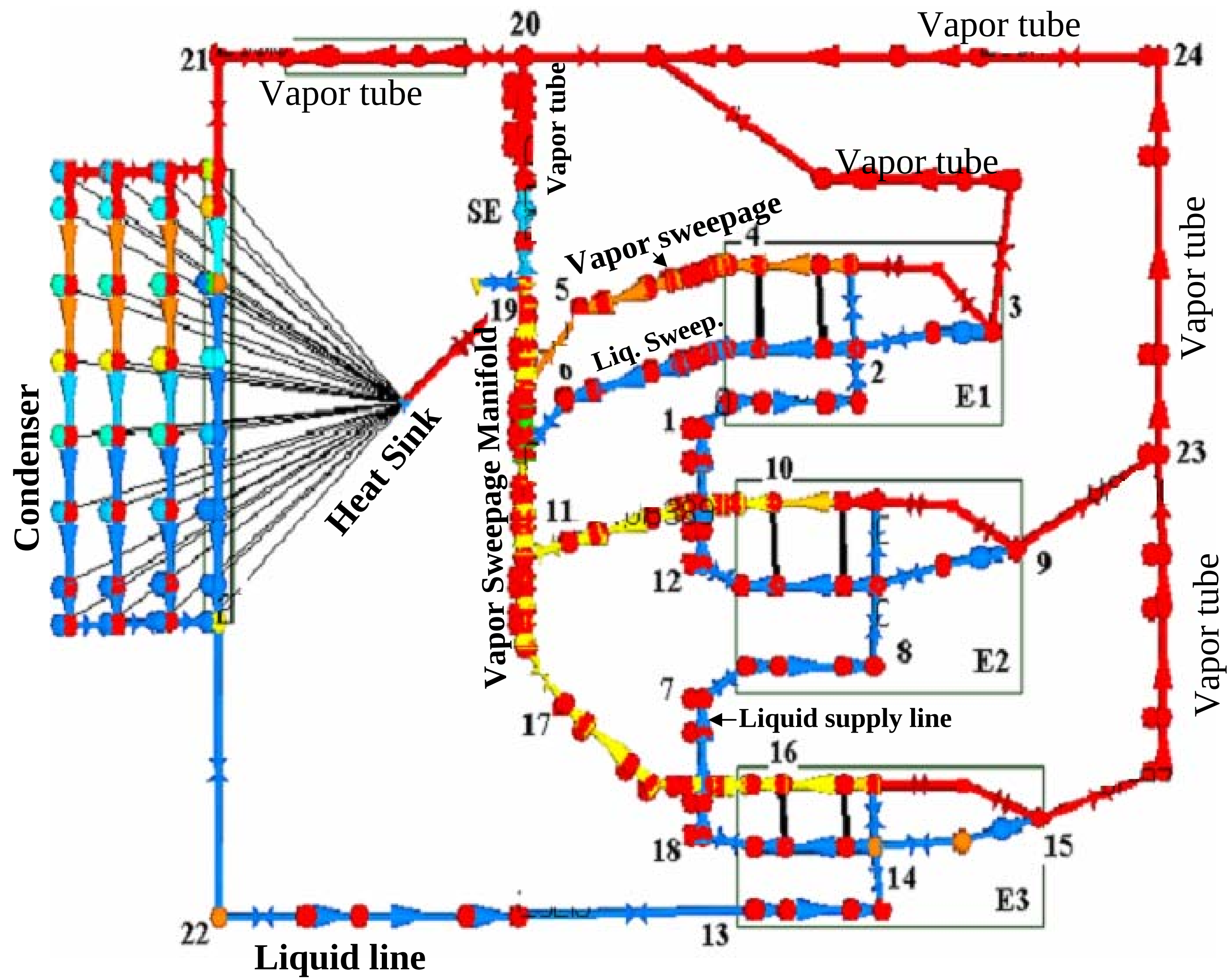


Schematics of the Configuration with Three main and one Secondary Evaporators Connected in Series (E3-E2-E1) via the Liquid Supply





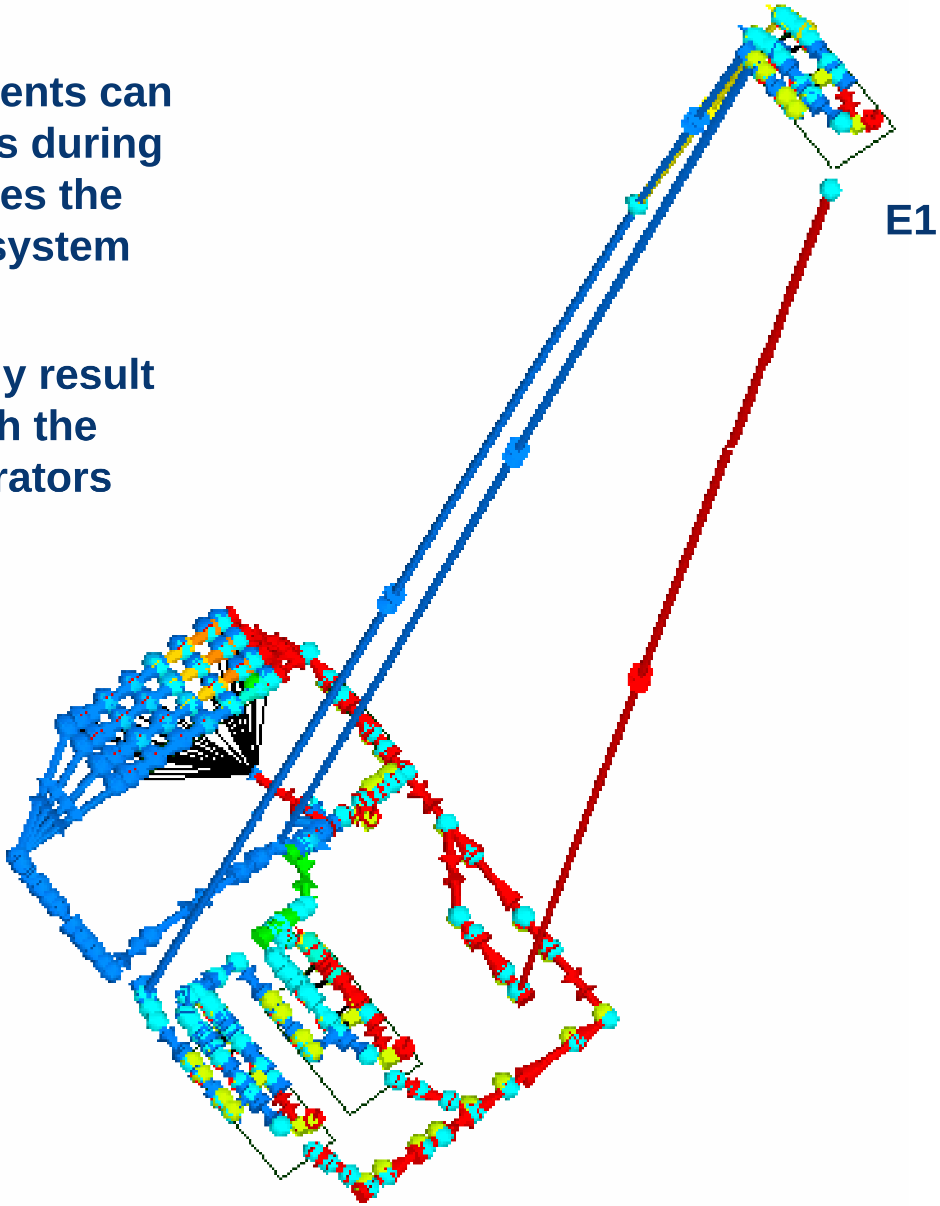
Graphical Representation of the Model and Lump Numbers for the Series Configuration



System with E1 elevated using CAPPMP and CAPIL

Some of the system components can be elevated versus the others during ground testing, which changes the pressure distribution in the system due to the liquid head.

Gravity effects can potentially result in the liquid breaking through the primary wick of lower evaporators



System Limitations and Operational Regimes Identifiable through Modeling

- Exceeding maximum capillary pressure for (a) primary wick, and sometimes (b) secondary wick
- Flowing the liquid through the primary wick of the lowest evaporator
- Sweepage flow insufficient to remove the vapor bubbles due to the back conduction: (a) Uneven flow distribution, and/or (b) Reverse sweepage flow
- Flow regimes: single-phase core versus nucleated core depending on the subcooling of the liquid entering an evaporator

Typical modeled cases (example) for the series configuration

No.	E1 heat load (W)	E2 heat load (W)	E3 heat load (W)	SE heat load (W)	Modeling result	Experimental result
1	250	250	250	60	Successful but reversed sweepage on E1	Worked with reversed sweepage on E1 observed
2	100	100	100	60	Successful but low sweepage on E1	Worked
3	50	50	50	60	Successful but pressure drops are very small	Worked
4	400	400	400	144	Reliable operation predicted	Worked
5	400	400	400	60	Reversed sweepage on E1 predicted	Worked at first, E1 failed after 20 minutes
6	400	400	400	144	E1 elevated by 1 m, successful	Worked
7	550	250	250	60	Uneven heat load, successful	Not tested

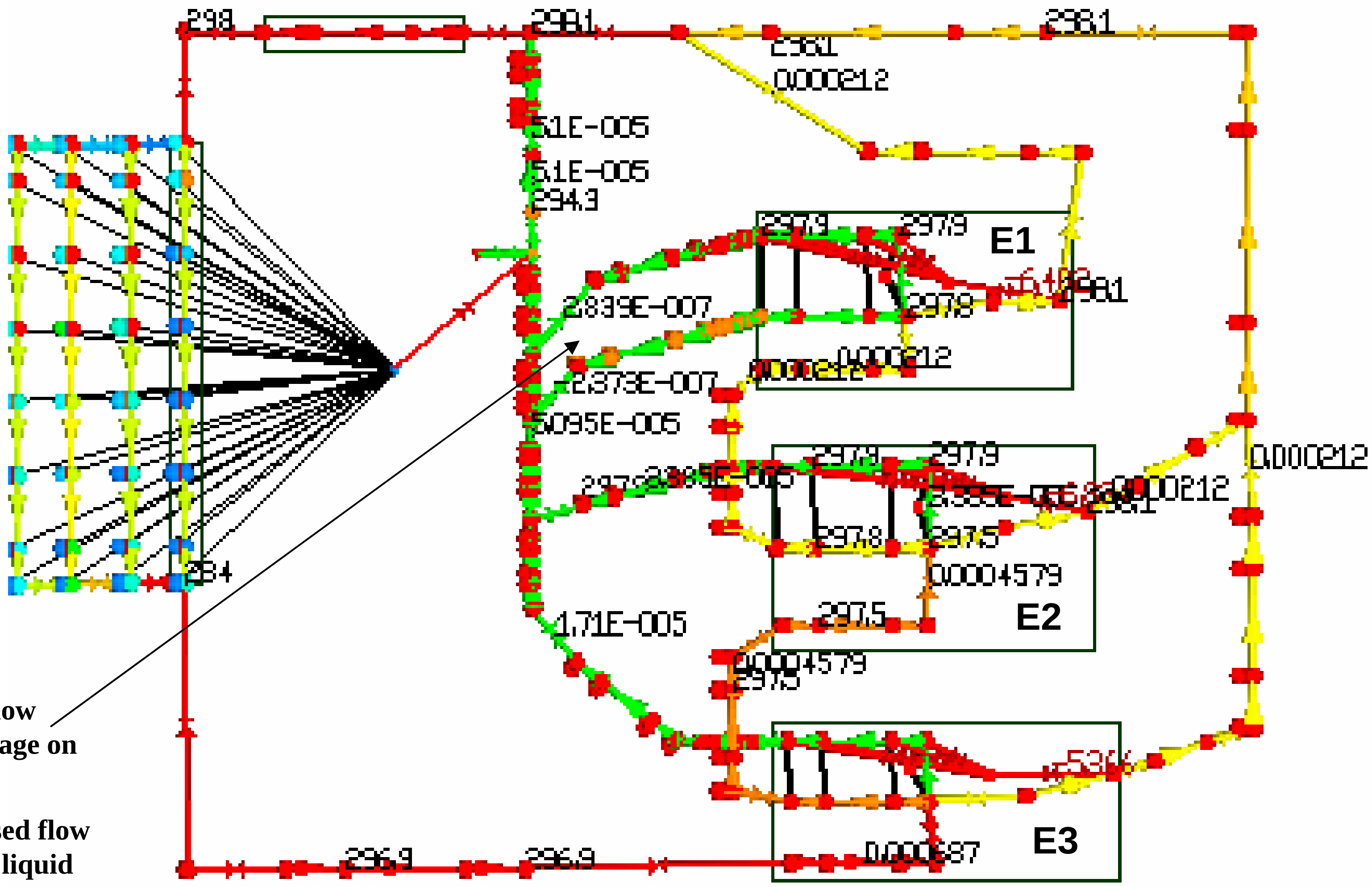
Model predictions qualitatively confirmed by experimental results
The model predicted flow reversal in the sweepage lines of E1

Case #1 Modeled: E1, E2,and E3 loaded with 250 W each and SE loaded with 60 W (Series, E3-E2-E1, with Ammonia)

OBSERVATIONS (results are shown in the next three slides)

1. **This case runs with 1.2 K of the liquid subcooling for the liquid entering E3 and no vapor in the sweepage lines**
2. **Although there is some sweepage on E1, the liquid sweepage line has a reversed flow in it. E1 exchanges pure liquid with the line connected to the reservoir.**
3. **The system can probably run for some time under such conditions, however its stability is compromised due to the reversed sweepage flow. The potential failure mechanism can be accumulation of vapor inside the core of E1, causing dryout of the primary wick.**

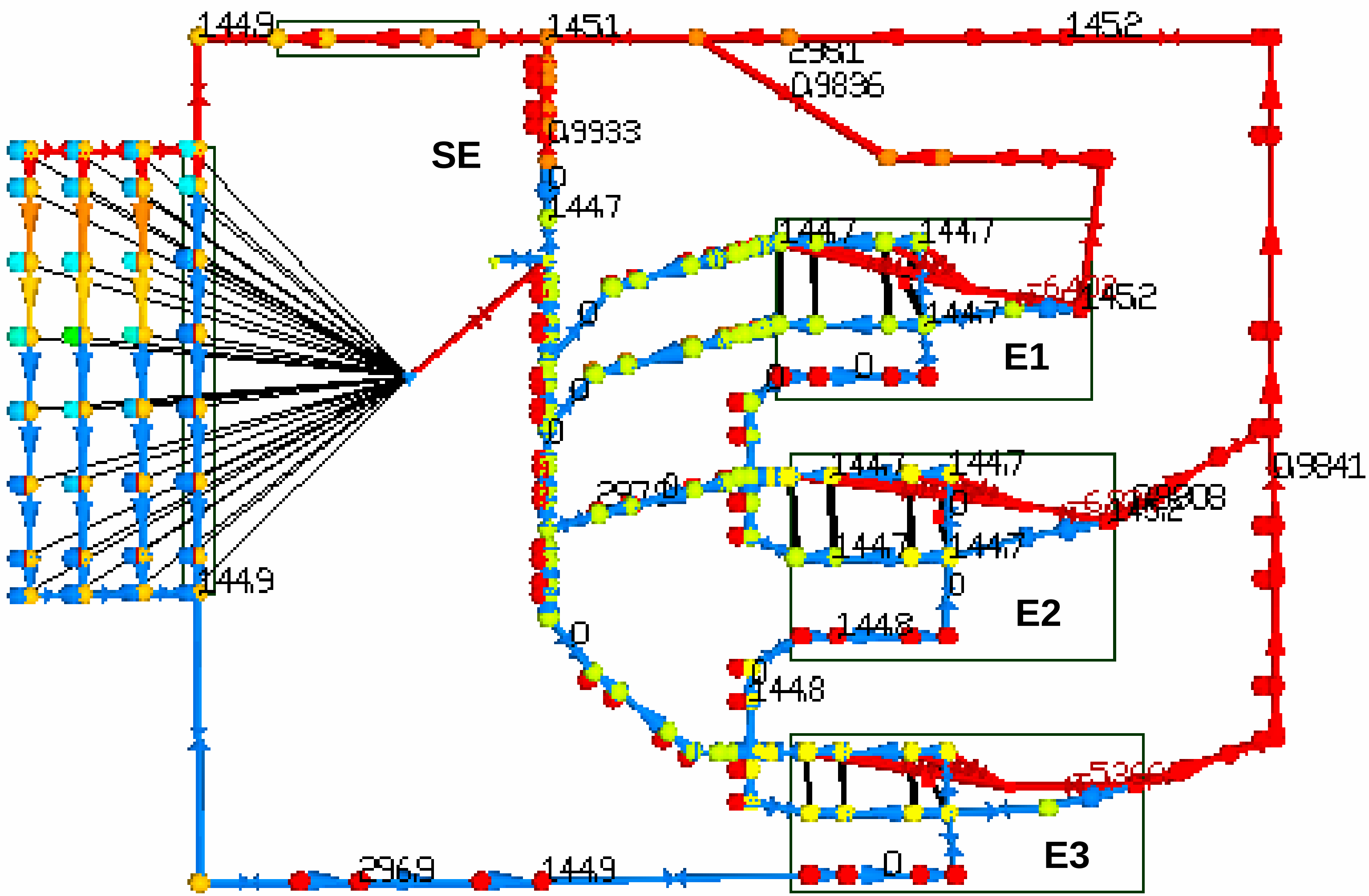
Temperatures and mass flow rates for the case #1



Very low sweepage on E1,

reversed flow in the liquid sweepage line

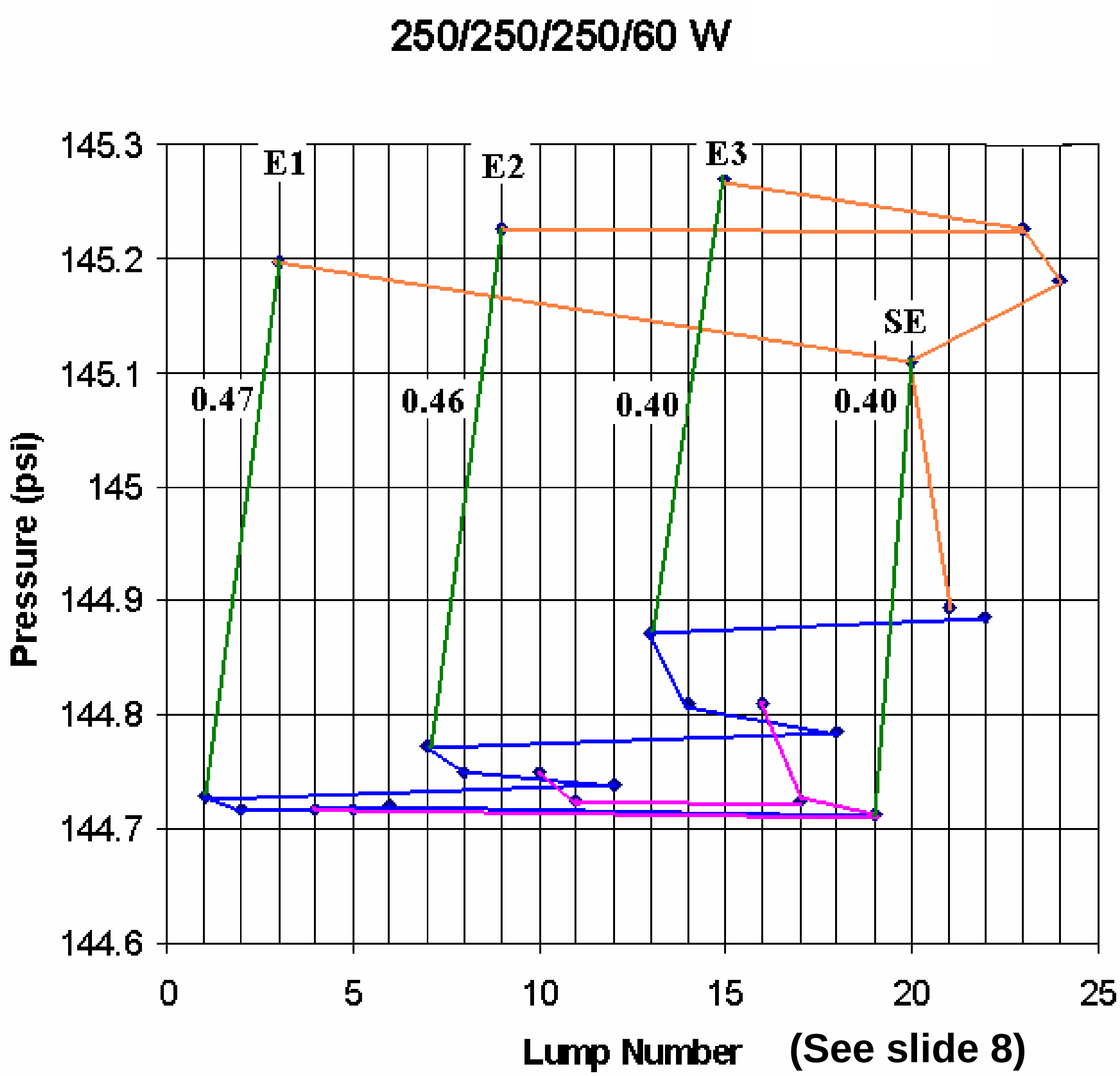
Pressures and flow quality for the case #1



Single-phase flow in the liquid supply and sweepage lines.

(Three nodal temperatures are shown for reference)

Pressure Distribution for the case #1



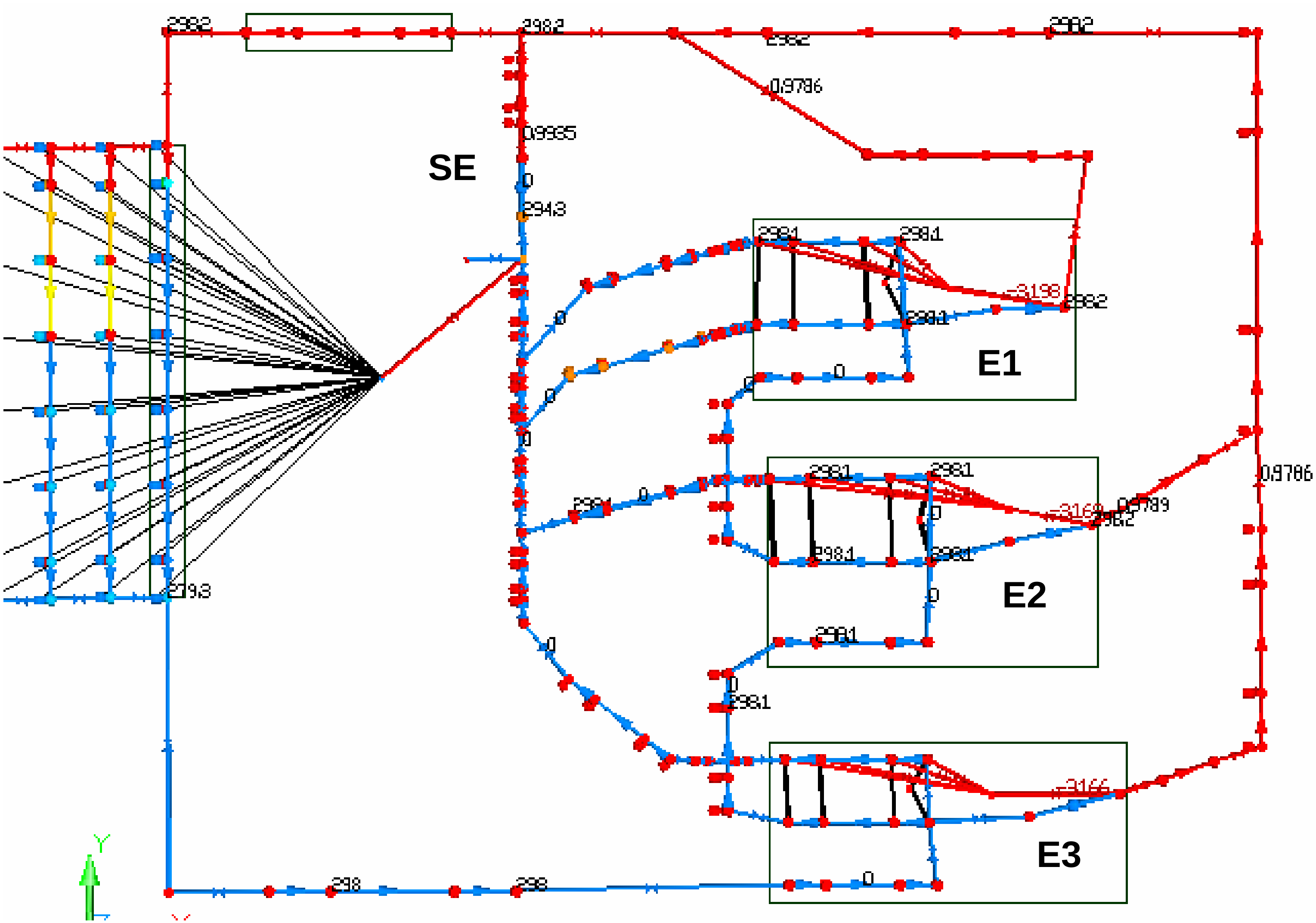
(See slide 8)

Case #2 with 100 W on the primary evaporators and 60 W on the secondary evaporator (with ammonia)

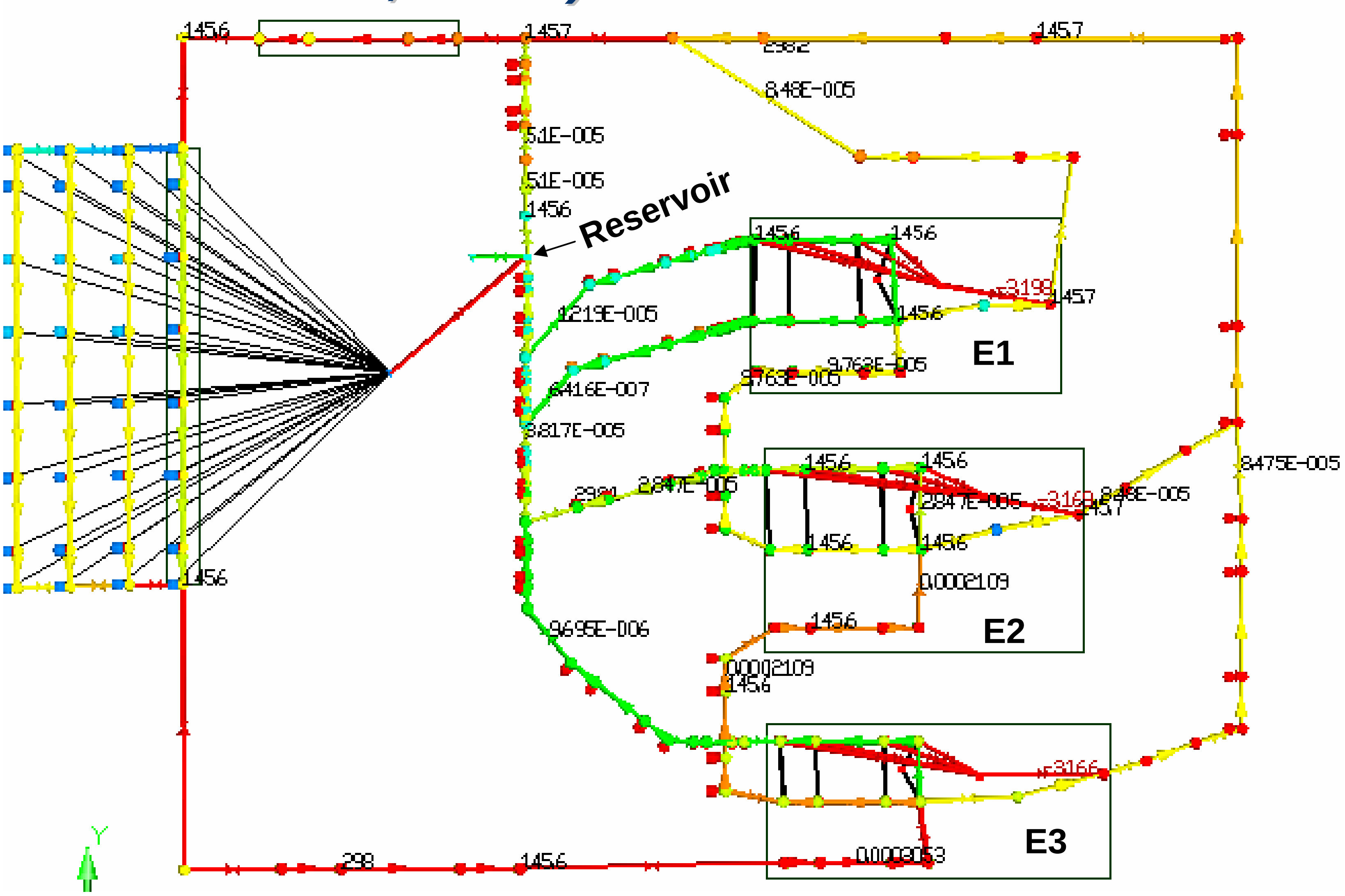
OBSERVATIONS (see results in the next three slides)

1. **This case runs with 0.2 K of the subcooling and no vapor in the sweepage lines**
2. **Sufficient sweepage for E1**
3. **The predicted pressure drops between the components are very low, which can potentially lead to calculation inaccuracies**

Temperatures and flow quality for the case #2 (100/100/100/60 W, series)

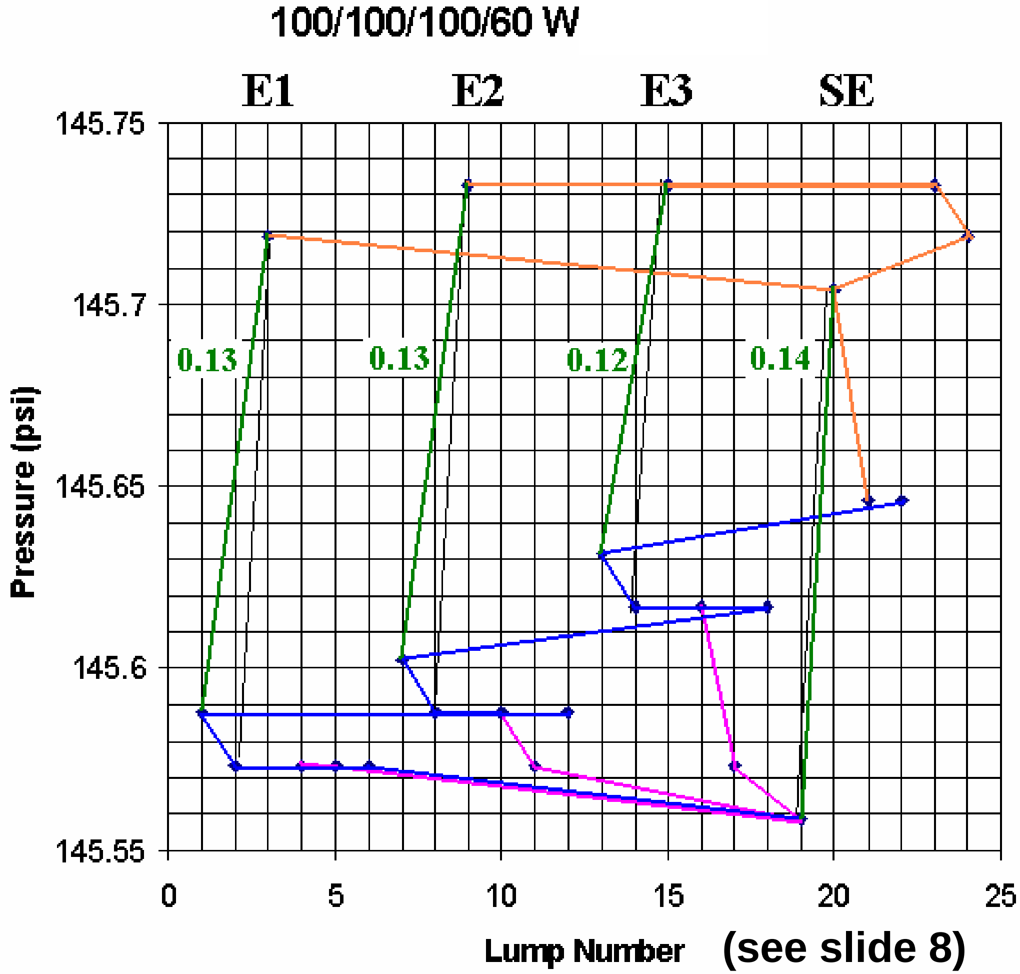


Pressures and mass flow rates for the case #2 (100/100/100/60 W , series)



Positive sweepage on E1 ensures reliable operation of the system

Pressure Distribution for the case #2



(see slide 8)

Example of the Preliminary Comparison of the pressure drops (psi) between the test data and calculations

Heat load per evaporator	E1 dP (psi)	E2 dp (psi)	E3 dp (psi)	SE dp (psi)	BPR dp (psi)	Delta-P on M-valve (E3) (psi)
CASE 1: 100 W per evap. <u>experimental</u>	0.52	0.64	0.39	0.7		
100 W per evaporator <u>predicted</u>	0.56	0.52	0.35	0.58	0.19	0.087 Swagelock 0.088 S/F
CASE 2: 250 W per evap. <u>experimental</u>	0.95	1.17	0.89	1.1		
250 W per evaporator <u>predicted</u>	1.27 (33%)	1.23	0.72	1.19	0.19	0.294 Swagelock 0.300 S/F

Pressure drops were predicted with a reasonable accuracy

CONCLUSIONS

1. A steady state Sinda-Fluint (Thermal Desktop™) model was created for a two-phase capillary-driven system with three main and one secondary evaporators. The model was qualitatively confirmed by comparison with the test data.

2. While most of the solutions for three evaporators in series predicted single-phase flow (pure liquid) in the sweepage lines, two-phase flow in the sweepage lines was also predicted for some practical cases and observed in the experiments.

3. The model predicted reliable operation of the system with both even heat load (for example 100/100/100 W) and uneven heat load (for example 250/250/500 W) between the main evaporators, which was demonstrated by the experiments

4. The model predicted successful operation of the system with one evaporator elevated and the test confirmed the predicted pressure distribution