Loop Heat Pipe Operation Using Heat Source Temperature for Set Point Control

Jentung Ku
NASA Goddard Space Flight Center
Greenbelt, Maryland
301-286-3130
Jentung.Ku-1@nasa.gov

Kleber Paiva, Marcia Mantelli
Federal University of Santa Catarina
Florianópolis, Santa Catarina, Brazil

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Introduction

- **Loop heat pipes (LHPs) have been used for thermal control of several NASA and commercial orbiting spacecraft.**
- **The LHP operating temperature is governed by the saturation temperature of its compensation chamber (CC).**
- **Most LHPs use the CC temperature for feedback control of its operating temperature.**
- **There exists a thermal resistance between the heat source to be cooled by the LHP and the LHP's CC. Even if the CC set point temperature is controlled precisely, the heat source temperature will still vary with its heat output.**
- **For most applications, controlling the heat source temperature is of most interest.**
- **A logical question to ask is: "Can the heat source temperature be used for feedback control of the LHP operation?"**
- **A test program has been implemented to answer the above question.**

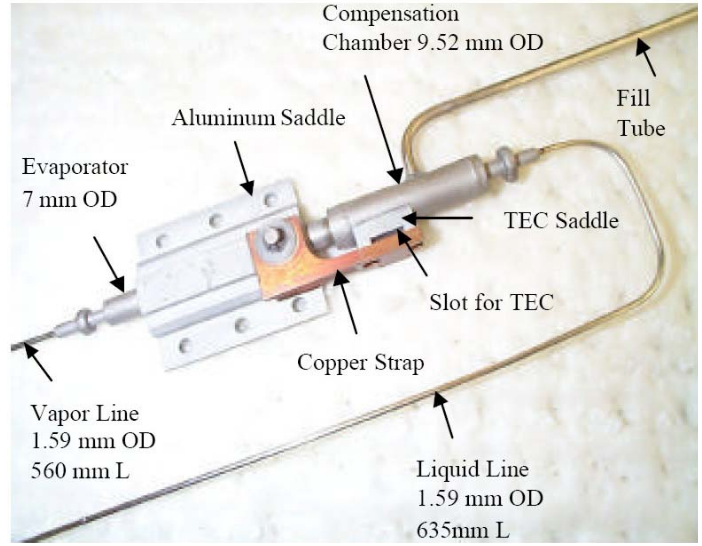
Test Program

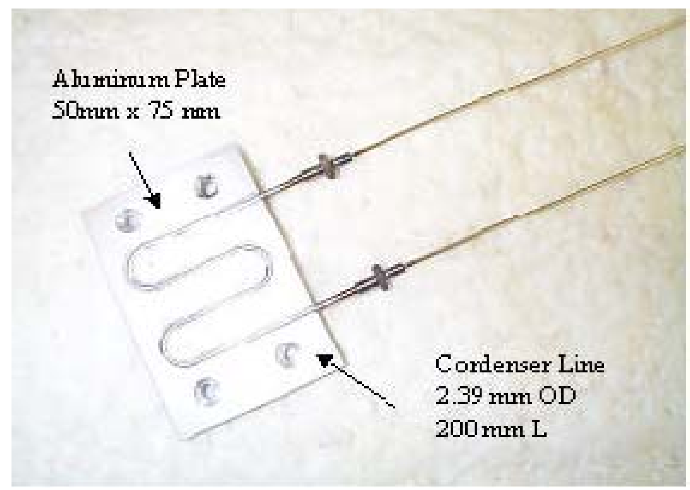
- **Objective**
  - **To investigate the LHP performance using the CC temperature and the heat source temperature for feedback control**
- **Test article**
  - **A miniature LHP built by Thermacore in 2003 under NASA's Cross Enterprise Technology Development Program (CETDP)**
  - **An aluminum thermal mass is attached to the LHP evaporator to serve as the instrument simulator.**
- **Test variables**
  - **Location of the temperature sensor used for feedback control of LHP operation: CC, evaporator, and thermal mass**
  - **Heat load to the thermal mass: 10W to 140W**
  - **Aluminum thermal mass: 110g and 350g**
  - **Thermal control device attached to the CC: thermoelectric converter (TEC) and electric heater (EH)**
  - **Temperature control scheme: PID (proportional–integral–derivative control) and on/off**
- **Only the results of PID control are presented.**

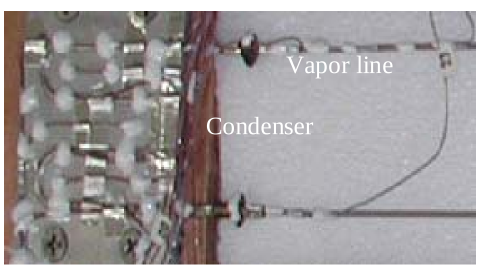
CETDP MLHP Design

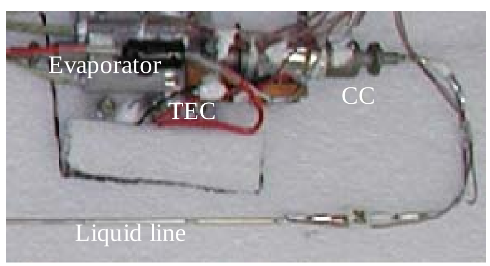
- **CETDP MLHP built by Thermacore - 2003**

Item	Description
Evaporator	SS - 6.35 mm O.D. x 51 mm length
	Aluminum Shell
Primary Wick	SS - 5.6 mm O.D. x 2.4 mm I.D
	1.2 µm pore size
	1.0×10^{-14} m^2
Secondary Wick	SS - screen, 400 x 400 mesh
Compensation Chamber	SS - 9.52 mm O.D. x 25.5 mm length
Vapor Line	SS - 1.59 mm O.D. x 610 mm length
Liquid Line	SS - 1.59 mm O.D. x 795 mm length
Condenser	SS tubing - 2.39 mm O.D. x 200 mm length Saddle: aluminum
Working Fluid	Ammonia, 1.5 g
Total Mass	79 g

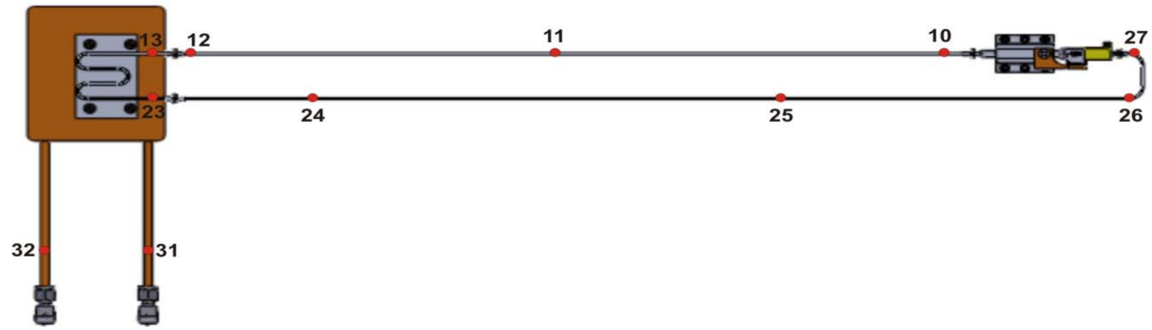


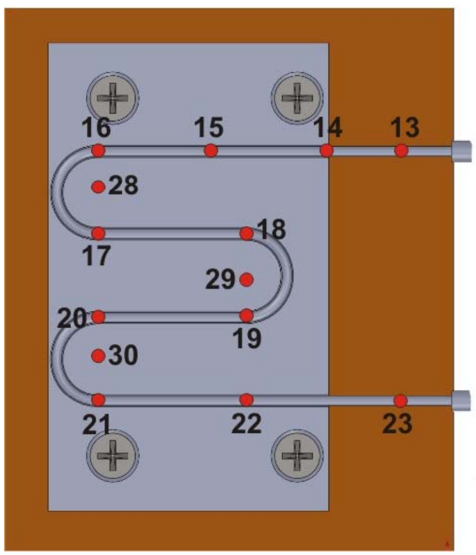






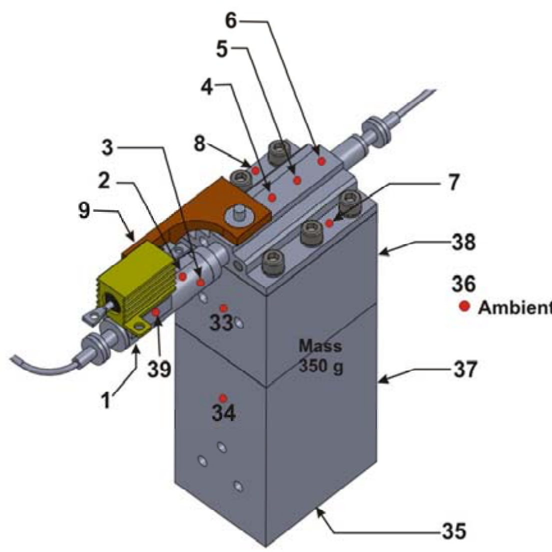
TC Locations





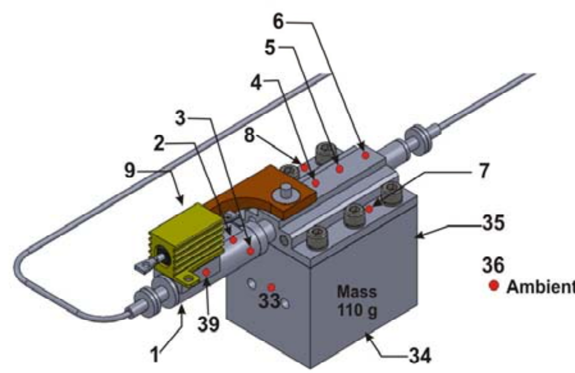
Condenser Section

Evaporator



Evaporator/CC with
Thermal Mass 1 (350g)

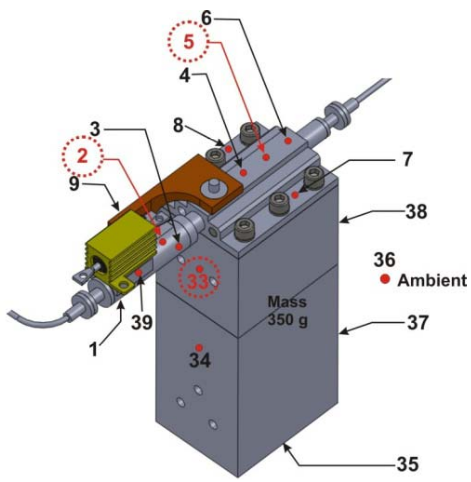
Evaporator

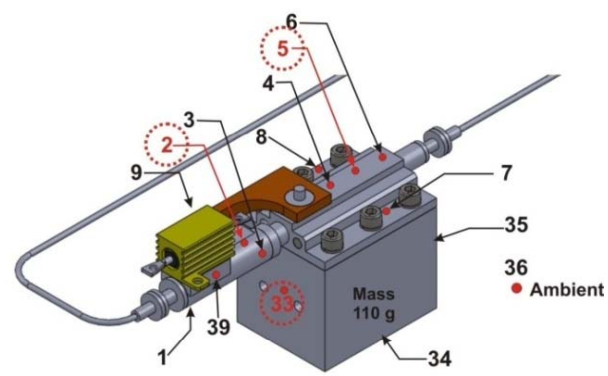


Evaporator/CC with
Thermal Mass 2 (110g)

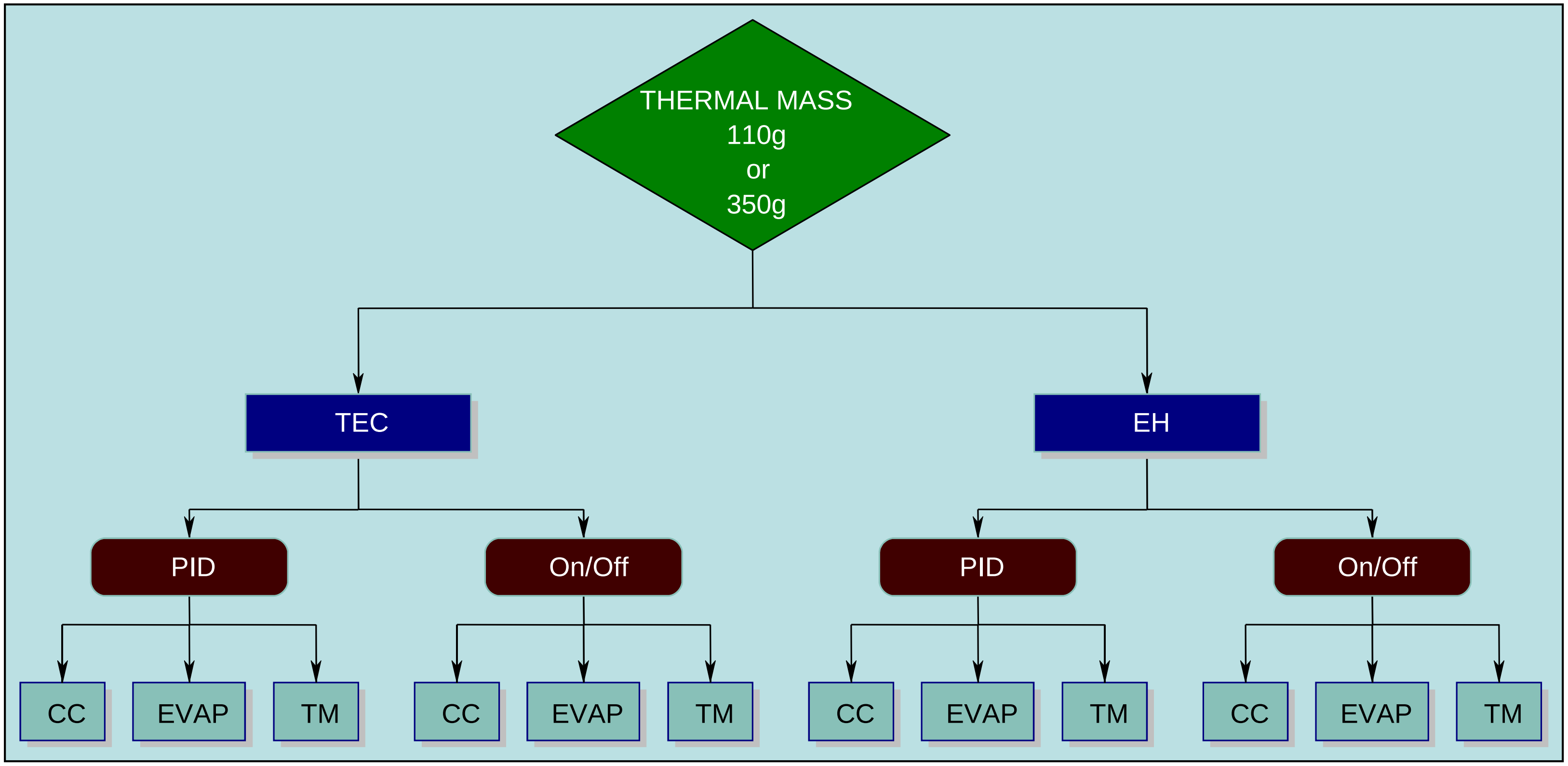
Location of Control Temperature Sensor

- **The location of the control temperature sensor for feedback control is shown below for conditions where 350 gram mass and 110 gram thermal mass were attached to the evaporator.**
  - **TC#2 on the CC**
  - **TC#5 on the evaporator**
  - **TC#33 on the thermal mass.**
- **Effect of high thermal resistance between thermal mass and LHP**
  - **A large thermal resistance was imposed between the thermal mass and the evaporator in this test (0.23 K/W or 4.4W/K).**
  - **High thermal resistance: TC #33 was used for feedback control**
  - **Near-zero thermal resistance: TC#5 was used for feedback control**





Test Variables

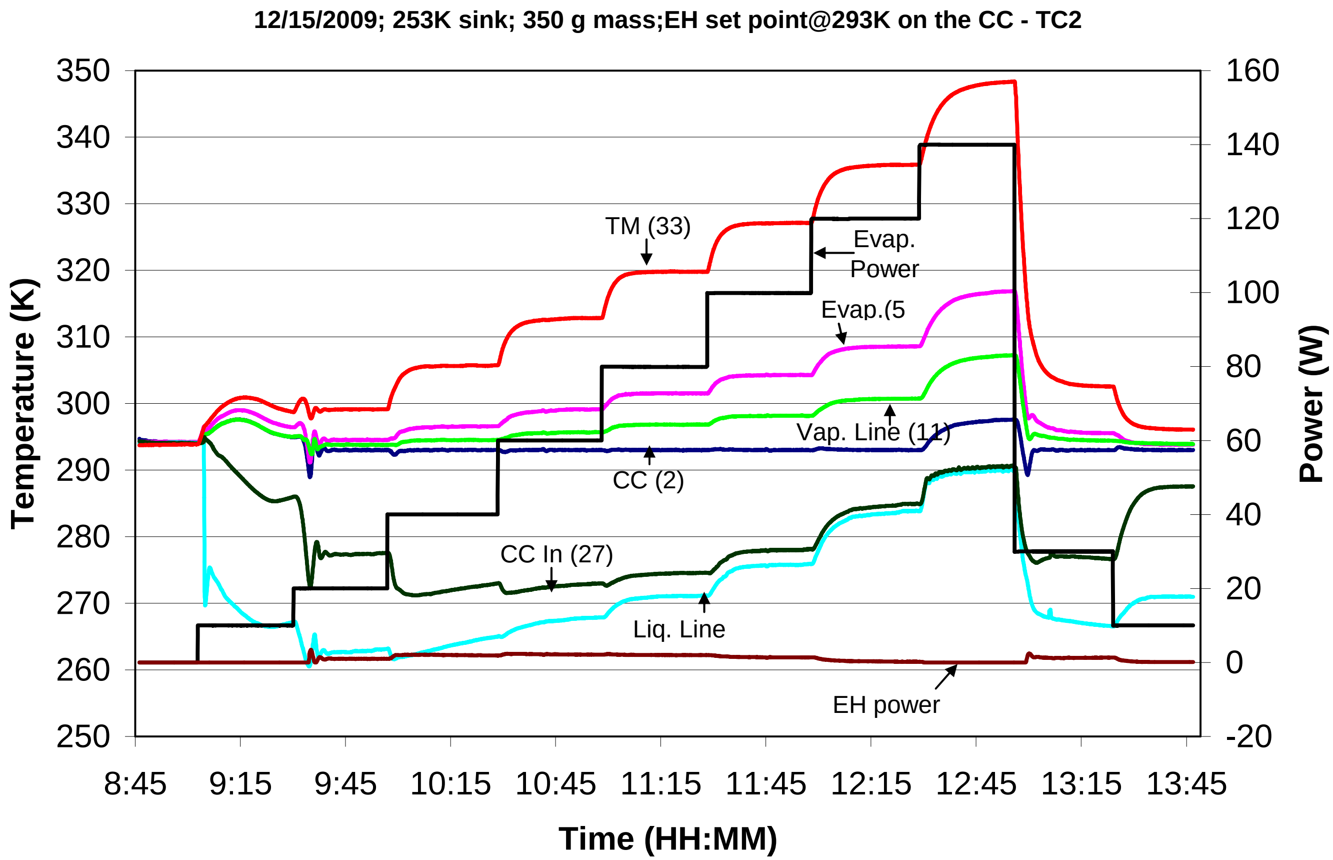


EH versus TEC

- The following charts show the effect of using LHP CC temperature and the heat source temperature for feedback control.
  - The CC was not preheated prior to start-up.
- Also shown are the effect of using TEC and electrical heater for CC temperature control.
- All tests employed the PID control scheme.
- No sophisticated control algorithm was used for transient operation.

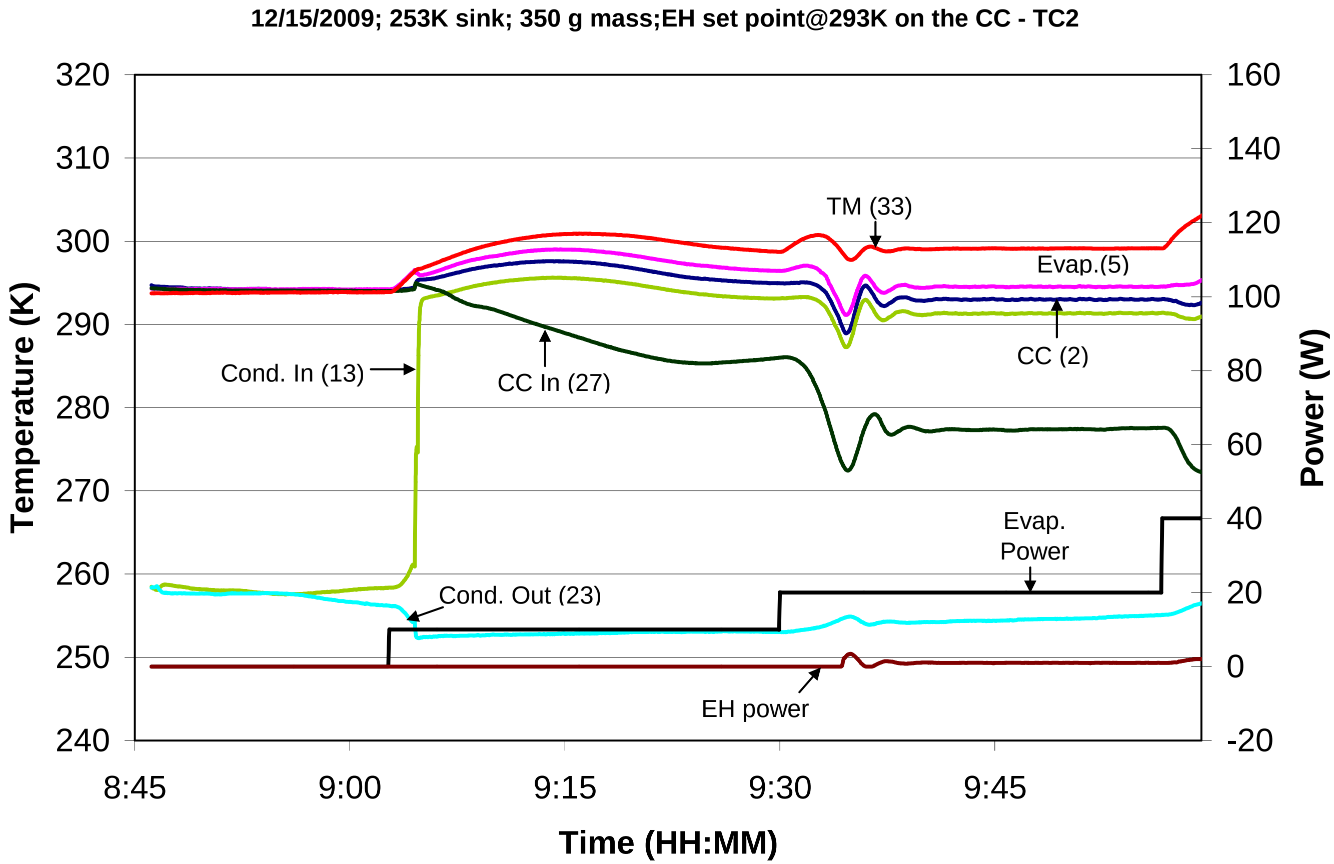
CC Controlled at 293K – EH/2W/PID/350g

- CC, evaporator and TM temperatures were stable between 20W and 120W.
- CC could no longer be controlled at 293K at 140W due to condenser limit (CC temperature rose to 297K)
- The start-up transient is shown in next slide



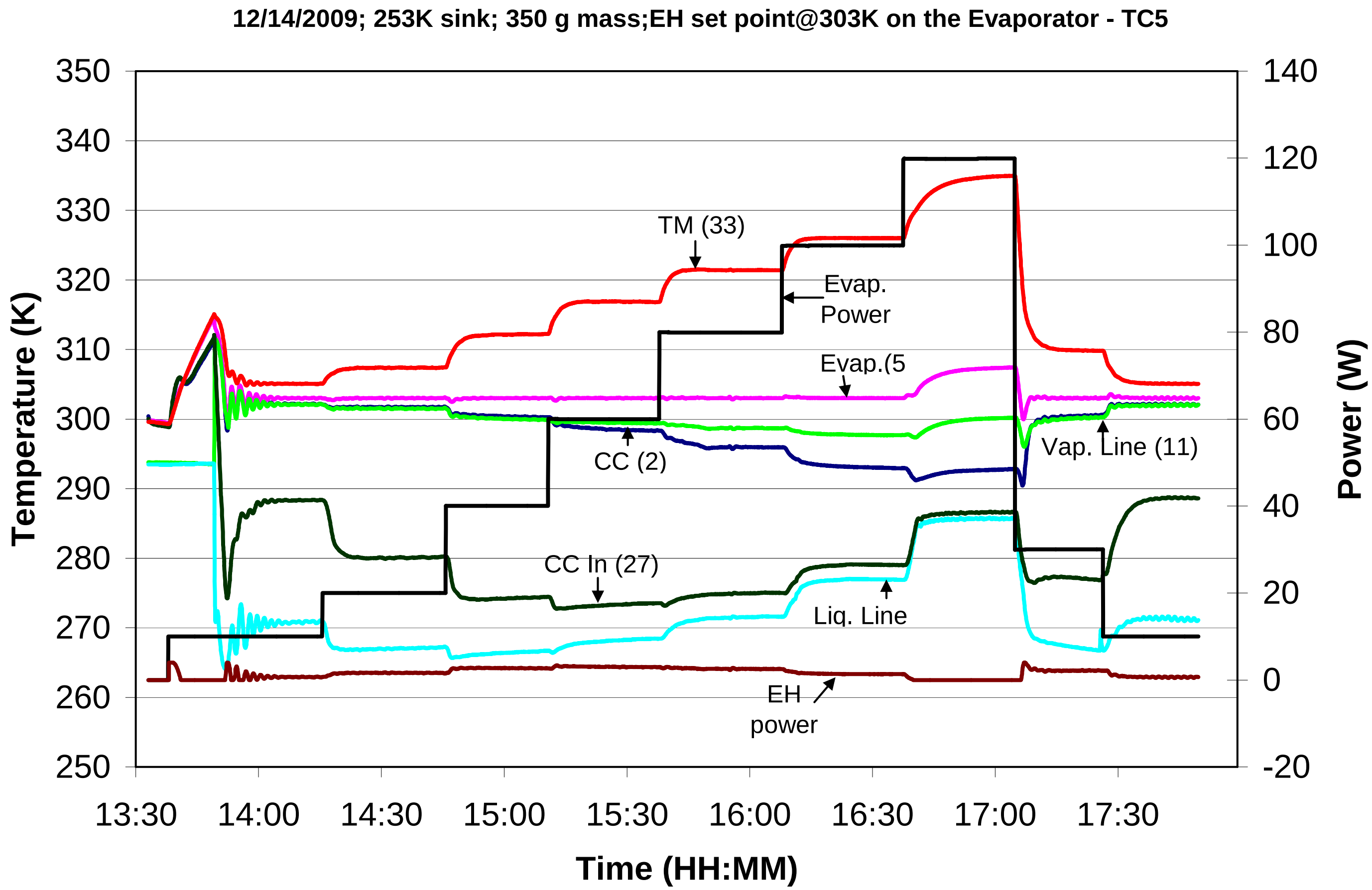
CC Controlled at 293K – EH/2W/PID/350g

- **Loop started as soon the power was applied to TM.**
- **Right after start-up, CC temperature rose because of the return of warm liquid.**
- **The CC eventually reached its natural operating temperature of 295K, higher than desired set point.**
- **During the transient from 10W to 20W, EH power (2W) was not enough to raise the CC temperature quickly.**



Evaporator Controlled at 303K – EH/3W/PID/350g

- **Simulated near-zero thermal resistance between heat source and LHP.**
- **Evaporator temperature was stable at 303K between 10W and 100W.**
- **The CC temperature decreased in steps between 20W and 100W in order to maintain evaporator at 303K.**
- **At 120W, the condenser limit was reached. The CC did not have enough subcooling to maintain the evaporator at 303K.**



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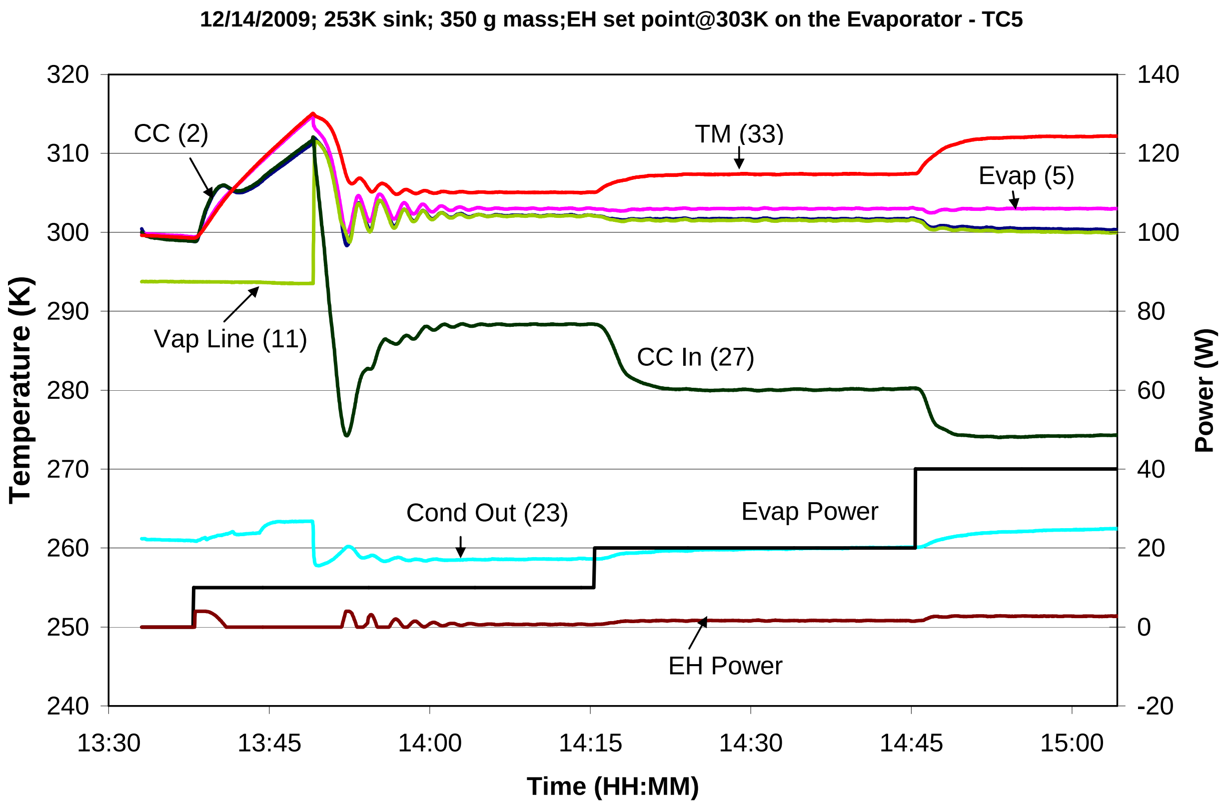
Evaporator Controlled at 303K – EH/3W/PID/350g

- Initially, CC/evaporator at 299K. As 10W was applied to evap, EH heated the CC because the evaporator set point was 303K.
- When the evaporator reached 303K, EH was deactivated. However, heat leak raised CC to 312K when the loop started with evaporator at 316K.
- Cold liquid led to CC temperature drop to 298K and evaporator to 300K. EH heated the CC until evaporator reached 303K. This was followed by a few more cycles of temperature oscillation, and loop eventually reached SS. TM sensible heat also contributed to the temperature oscillations.
- The loop was never shut down (vapor line TC 11 was at CC saturation temperature all the time).



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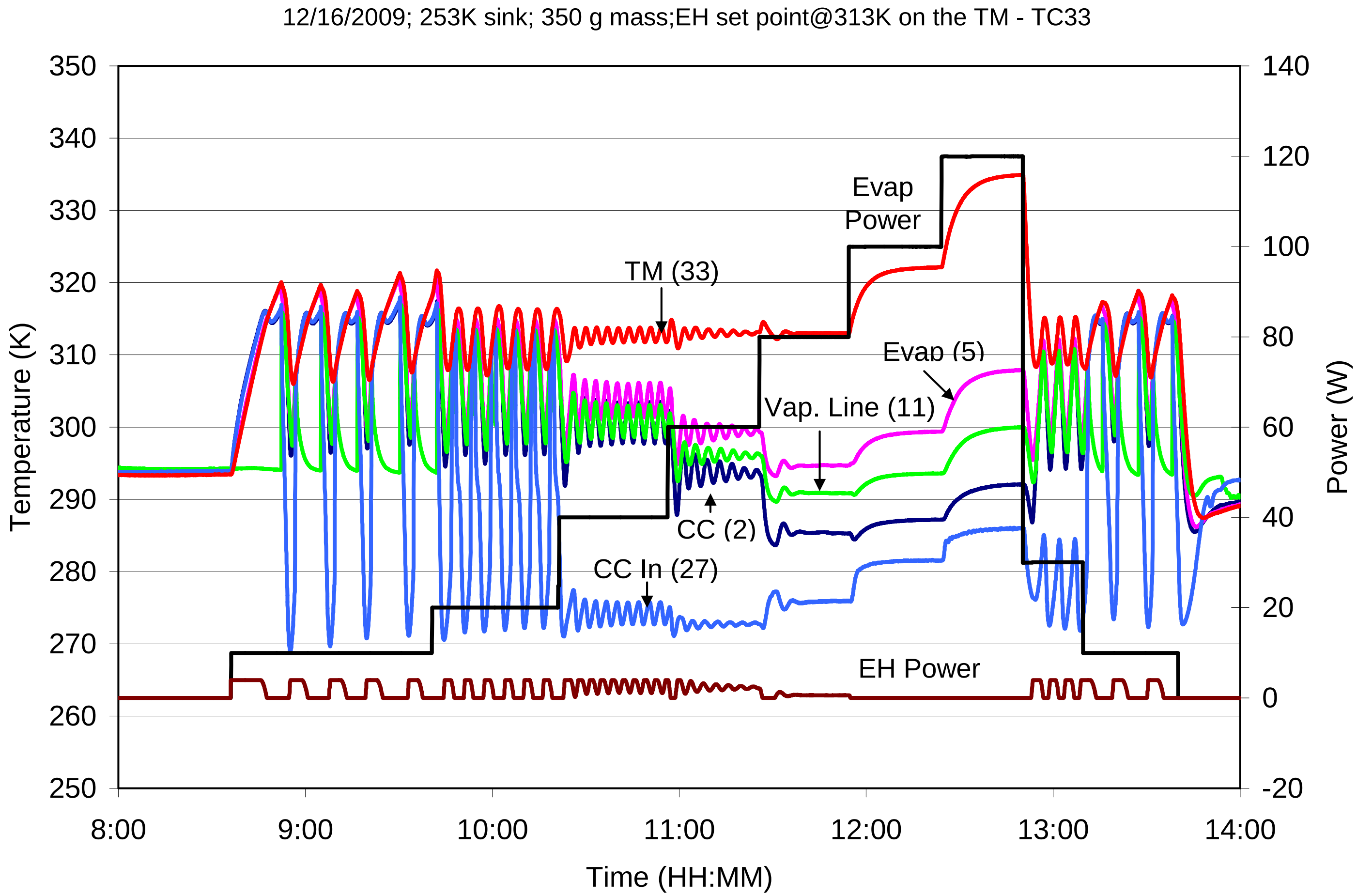
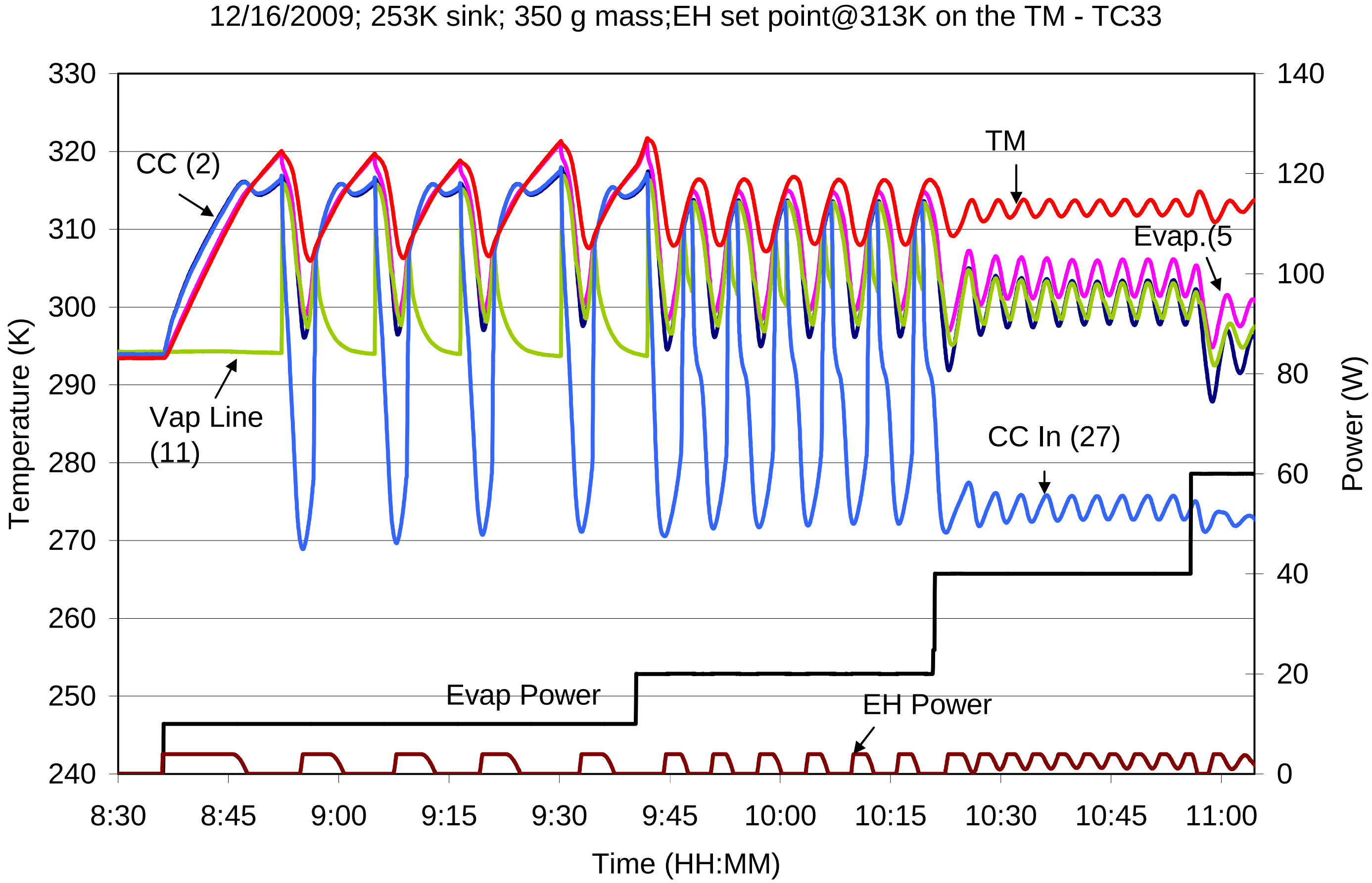
TM Controlled at 313K – EH/4W/PID/350g

- **At 10W, the loop repeatedly started and shut down (see next slide).**
- **At 40W, TM oscillated between 312K and 314K, less at 60W. No oscillation at 80W.**
- **At 100W, condenser limit and CC at 287K. 120W, condenser limit, CC at 292K.**
- **Temperature oscillations resumed at 30W and 10W (not just a start-up transient effect).**



TM Controlled at 313K – EH/4W/PID/350g

- Initially, CC, evaporator, and TM were at 294K.
- When 10W was applied to evaporator, EH was on to heat the CC. When TM reached 313K, EH was deactivated. However, CC temperature rose due to heat leak from the evaporator.
- As the loop started, CC temperature dropped to 297K due to cold liquid injection. TM was at 307K.
- EH heated the CC. The loop was shut down with 4W to CC and 10W to TM. The loop then repeated startup and shutdown.
- At 20W, the oscillation reduced. Loop did not completely shut down (TC 11 always followed TC 2) although forward/back flow alternated.



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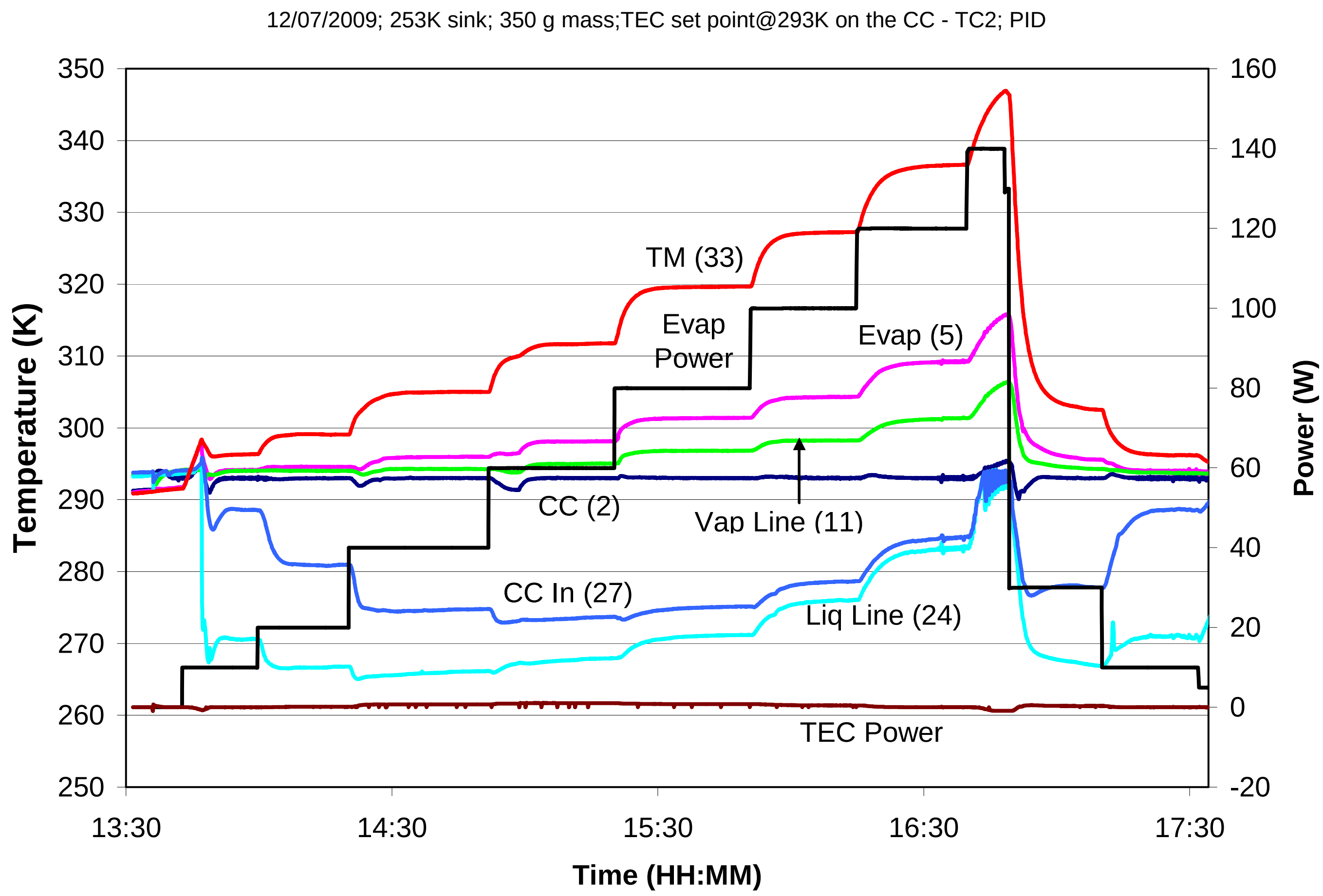
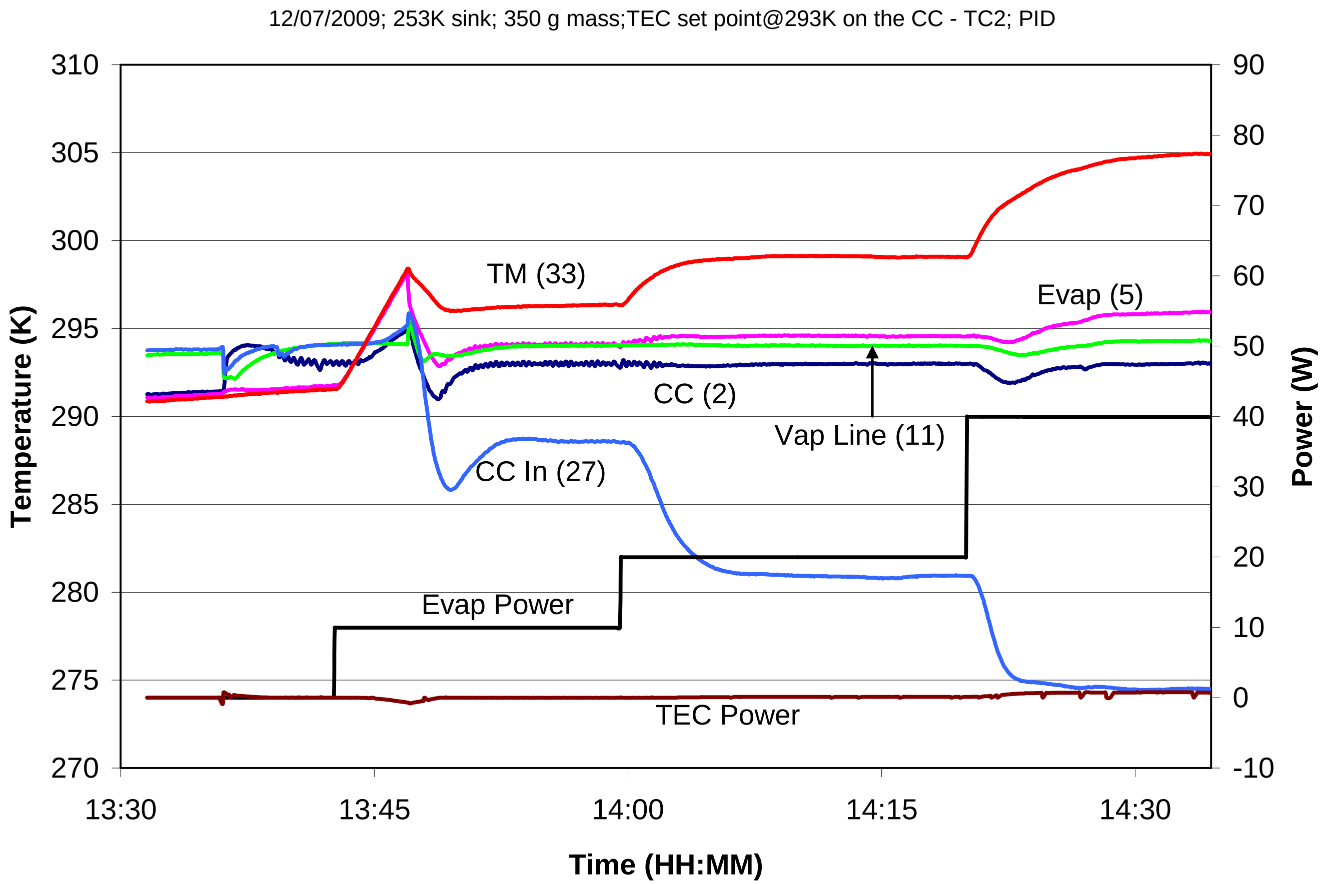
CC Controlled at 293K – TEC/1W/PID/350g

- **CC, evaporator, and TM temperatures were stable between 10W and 120W. CC and TM temperatures increased with increasing power.**
- **CC temperature dropped when the heat load increased from 20W to 40W and from 40W to 60W because 1W to TEC was not enough to heat the CC during the transient.**
- **At 140W, condenser limit was reached - TEC cooled the CC (negative TEC power).**
- **Performance was similar to that demonstrated in 2003 tests.**



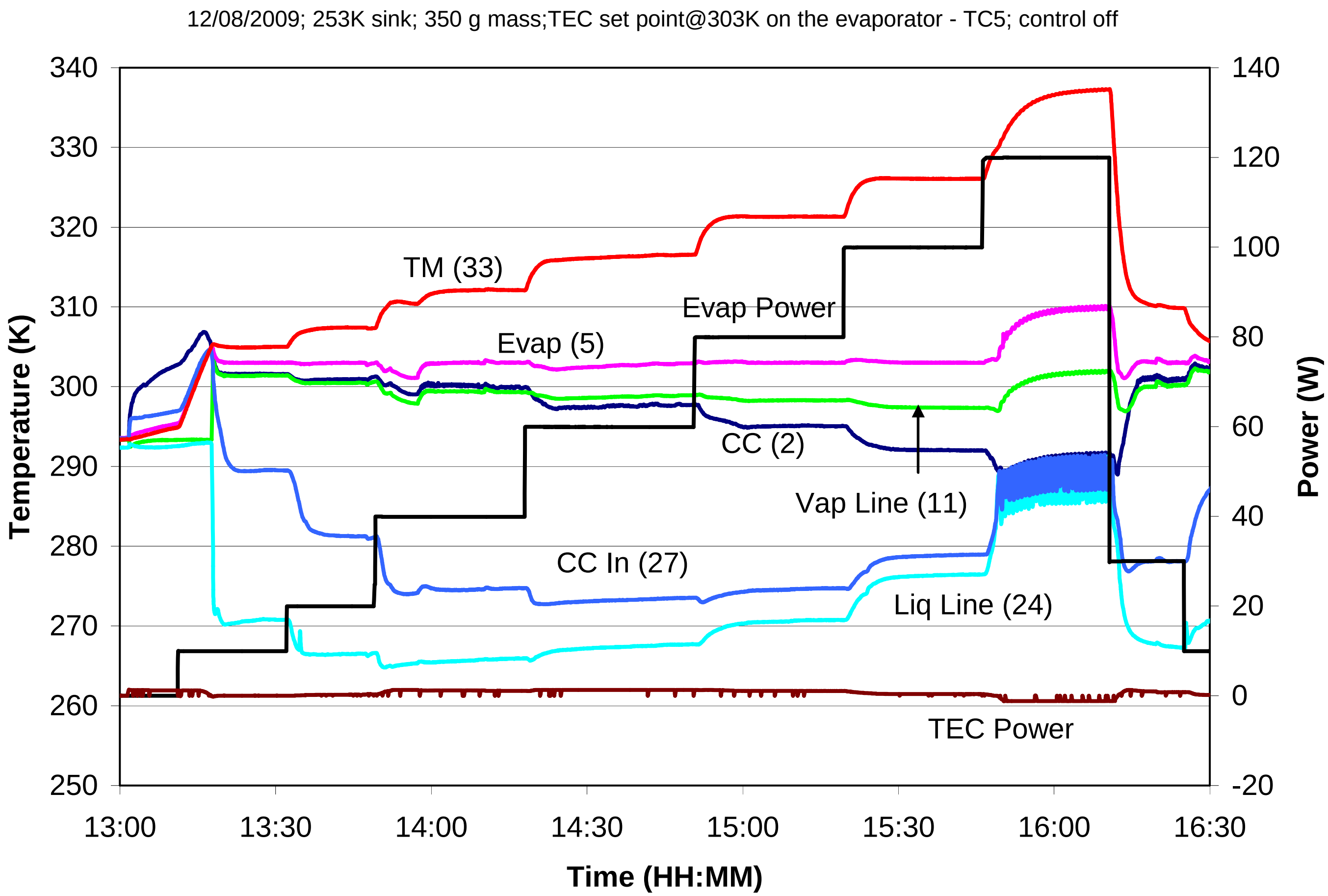
CC Controlled at 293K – TEC/1W/PID/350g

- **When 10W was applied to TM, CC temperature rose due to heat leak. TEC cooled the CC.**
- **As the loop started, CC temperature dropped due to injection of cold liquid. TEC raised CC temperature.**
- **The TEC power of less than 1W was not sufficient for CC temperature control during transients.**



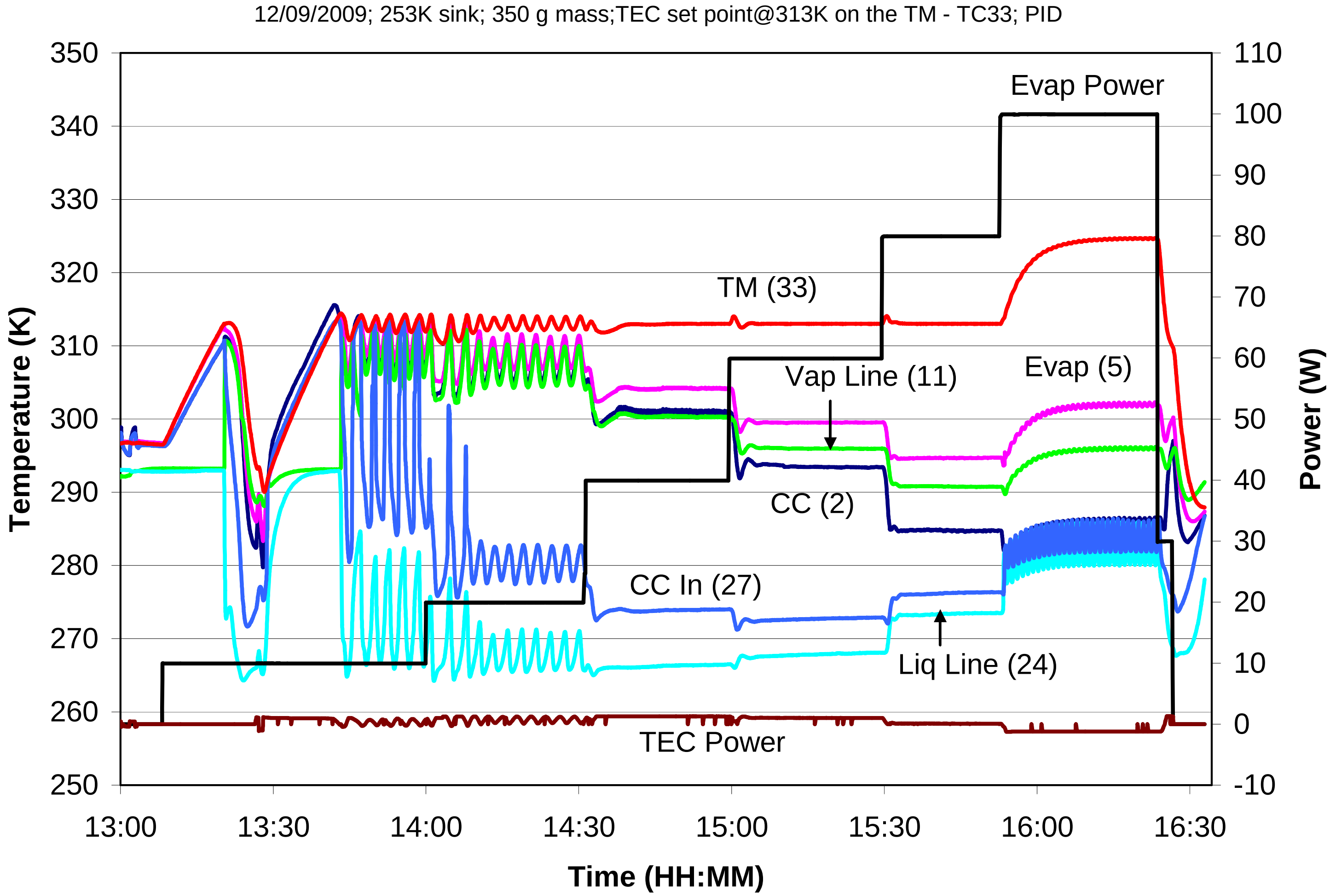
Evaporator Controlled at 303K – TEC/1W/PID/350g

- **Evaporator at 303K between 10W and 100W. CC, evaporator and TM temperatures were stable.**
- **At 120W, condenser limit – evaporator was above 303K. TEC cooled CC.**
- **Evaporator was controlled at 303K again when the heat load decreased to 30W and 10W.**



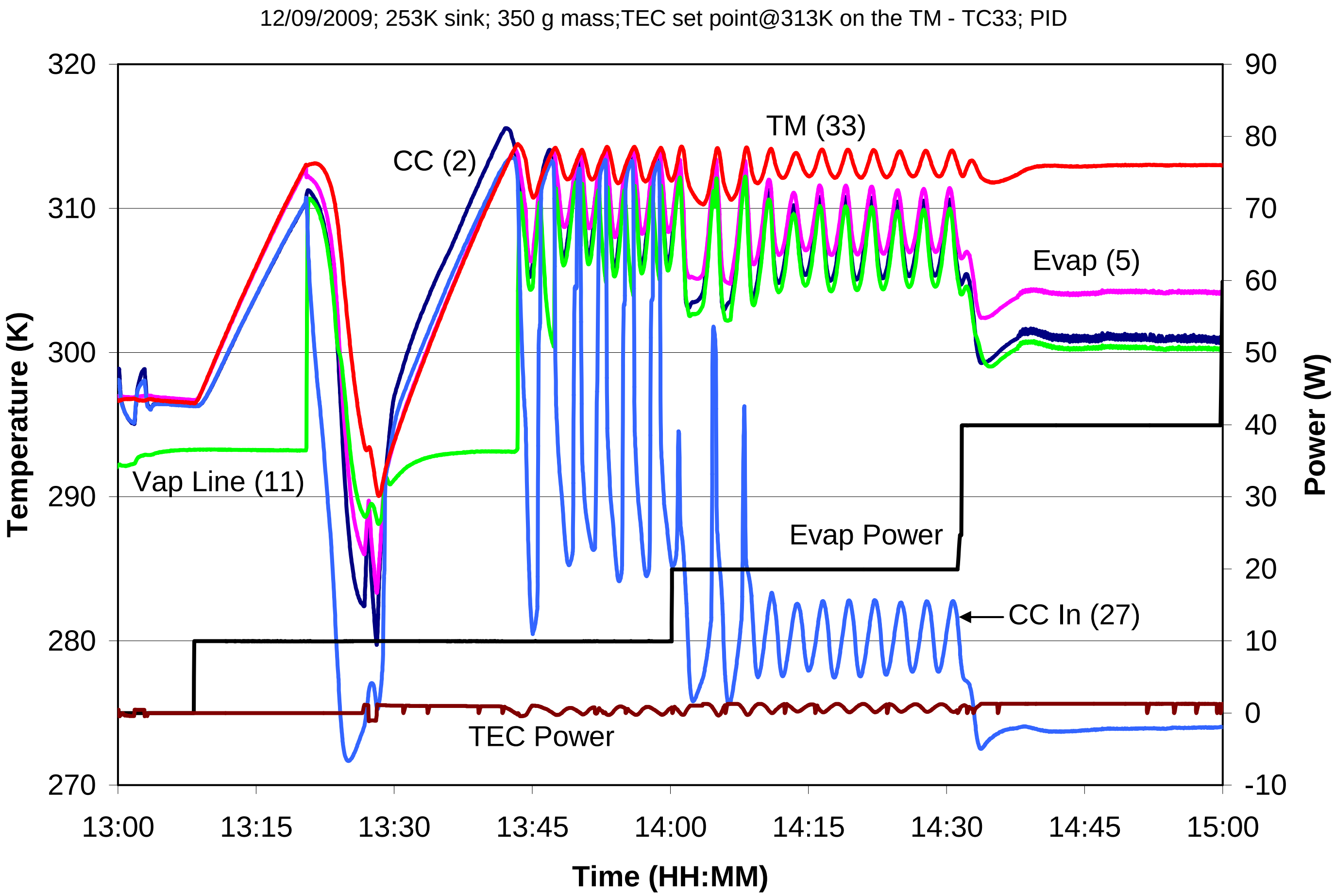
TM Controlled at 313K – TEC/1W/PID/350g

- TM at 313K between 40W and 80W. CC and evaporator temperatures dropped at each power increase.
- At 100W condenser limit – TEC cooled CC.
- Temperature oscillations between 10W and 20W. No oscillations at 40W and above.



TM Controlled at 313K – TEC/1W/PID/350g

- Initially with 10W to TM, TEC was turned on to heat CC until TM reached 313K.
- When the loop started, CC temperature dropped sharply due to cold liquid injection. TEC was turned on to heat the CC. With only 10W to the TM, the loop was shut down, followed by repeated start-up/shutdown cycles.
- At 20W, temperature oscillations occurred, but no repeated start-up/shutdown cycles.
- At 40W, no temperature oscillations.



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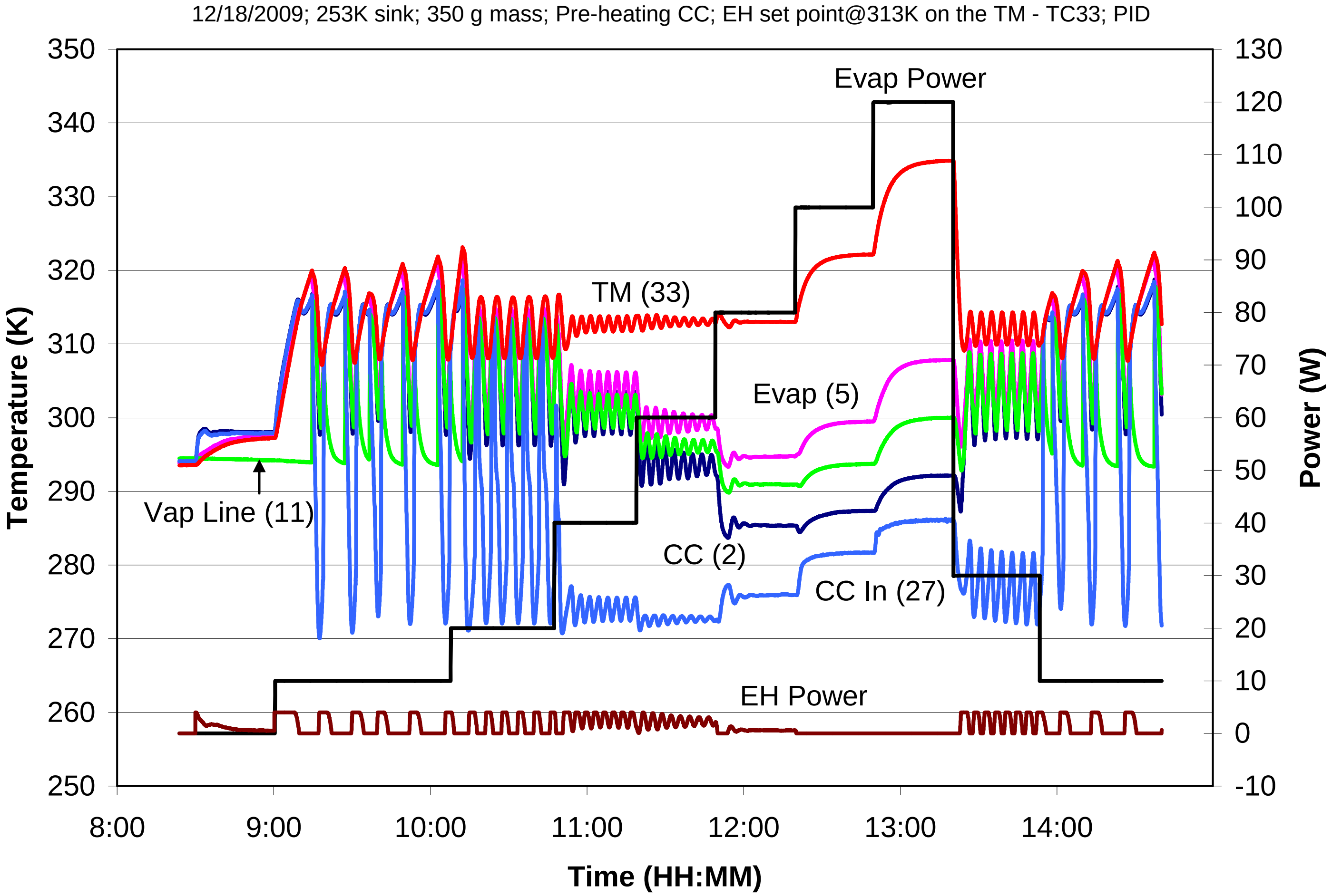
Pre-heating the CC prior to Start-up

- **In typically LHP applications, the CC was preheated prior to start-up to ensure the evaporator wick is fully wetted.**
- **The following slides show that pre-heating the CC did not have much effect on the temperature control when the control temperature sensor was placed on the heat source.**
- **Using the TEC resulted in better temperature control than using the electrical heater, mainly because the TEC could also provide cooling to the CC.**

TM Controlled at 313K (CC Preheated to 298K) – EH/4W/PID/350g

- At 10W, the loop repeatedly started and shut down (see next slide).
- At 40W, TM oscillated between 312K and 314K, less at 60W. No oscillation at 80W.
- At 100W, condenser limit and CC at 287K, TM at 323K. At 120W, CC at 292K and TM at 335K.
- Temperature oscillations resumed at 30W and 10W (not just a start-up transient effect).



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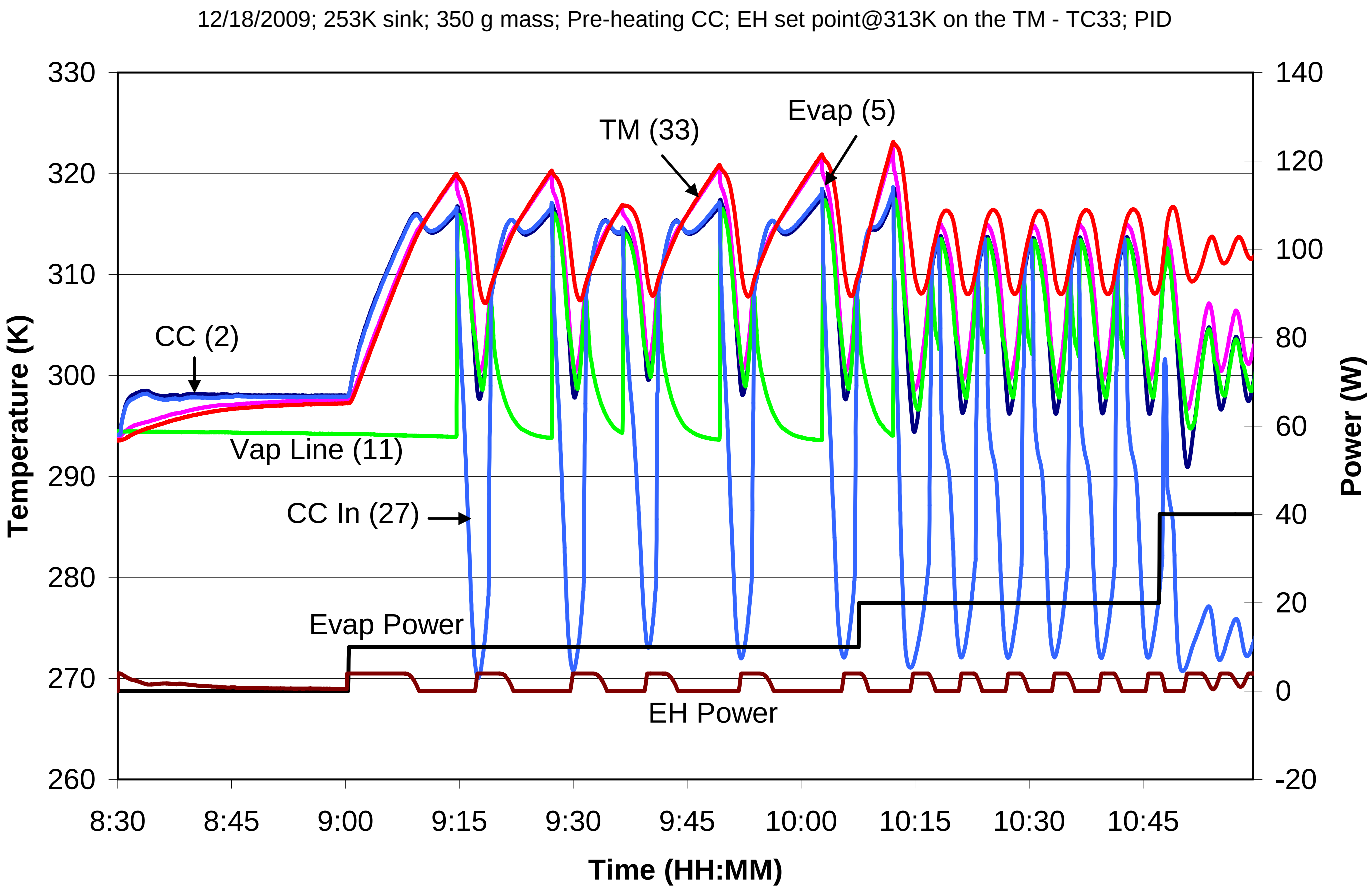
TM Controlled at 313K (CC Preheated to 298K) – EH/4W/PID/350g

- Initially, CC, evaporator, and TM were heated to 298K.
- When 10W was applied to evaporator, EH was on to heat the CC. When TM reached 313K, EH was deactivated. However, CC temperature rose due to heat leak.
- As the loop started, CC temperature dropped to 297K due to cold liquid injection. TM was at 306K.
- EH heated the CC. the loop was shut down with 4W to CC and 10W to TM. The loop then repeated startup and shutdown cycles.
- At 20W, the oscillation reduced. Loop did not completely shut down (TC 11 always followed TC 2) although forward/back flow alternated.



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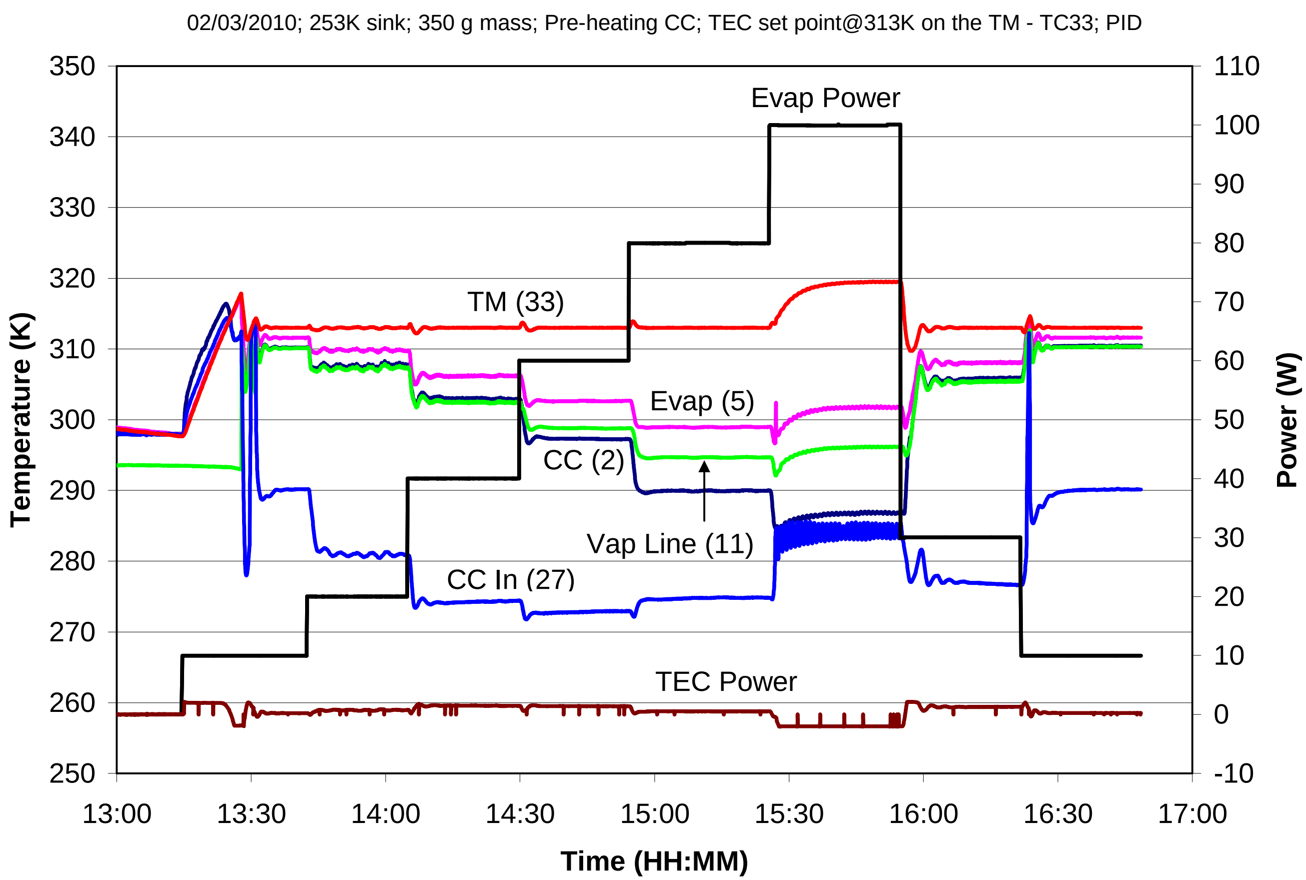
TM Controlled 313K (CC pre-heated to 298K) – TEC/2W/PID/350g

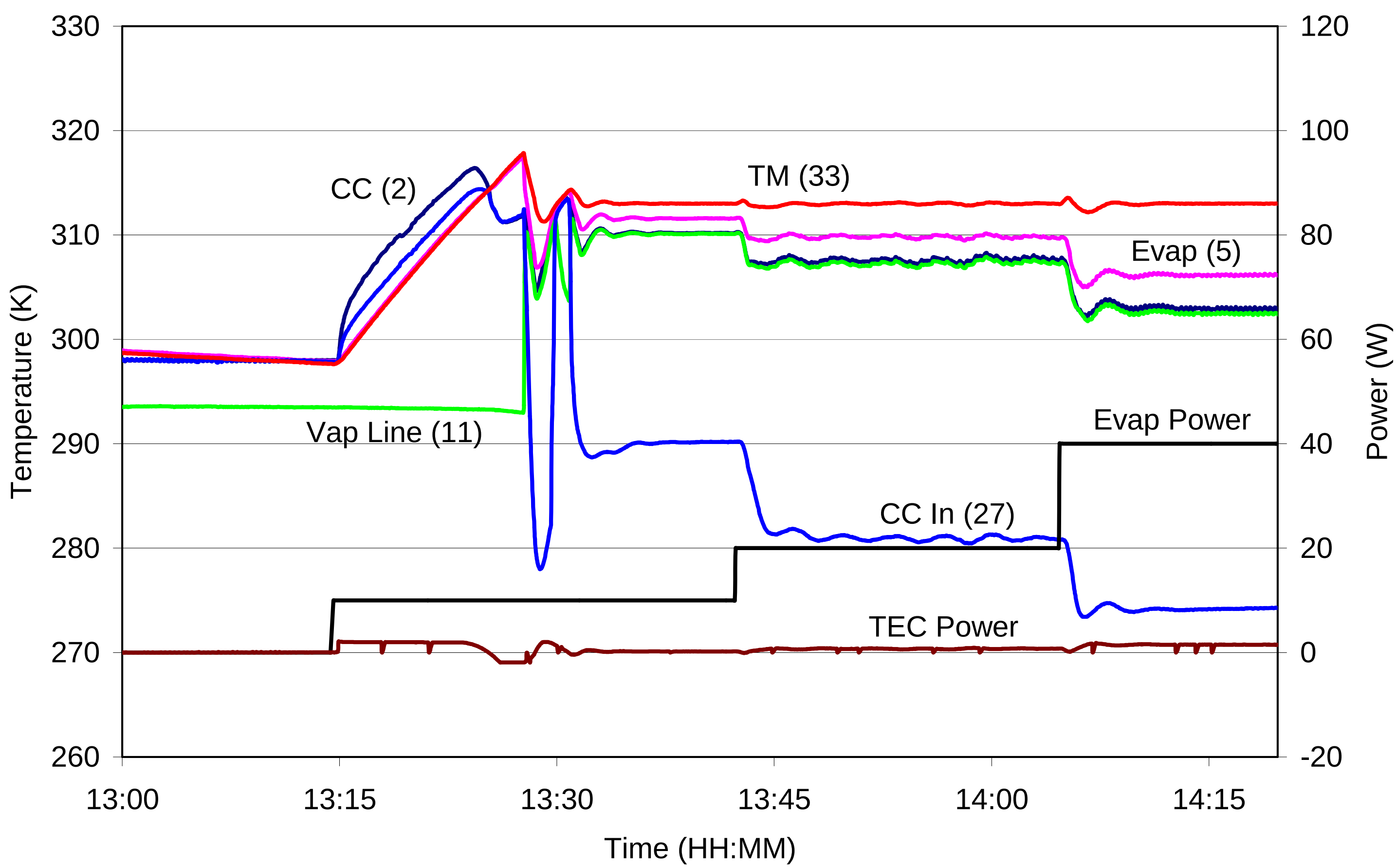
- **TM controlled at 313K between 10W and 80W – little oscillations**
- **At 100W - condenser limit**
- **TM controlled at 313K again as heat load lowered to 30W and 10W**



TM Controlled 313K (CC pre-heated to 298K) – TEC/2W/PID/350g

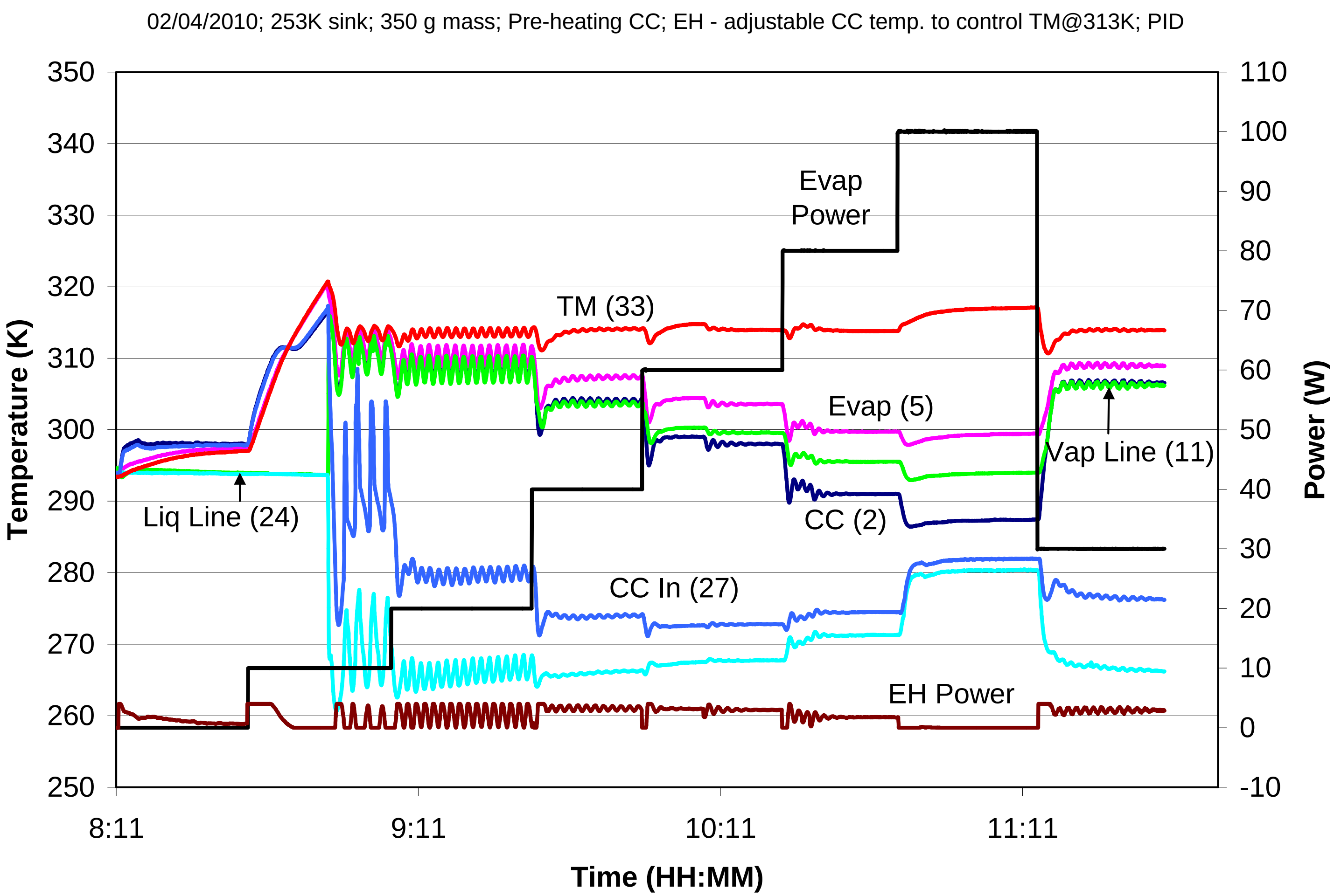
- **Initially TEC heated CC so that TM would be raised to 313K**
- **When TM reached 313K, CC was at 316K. TEC cooled CC (negative power).**
- **No repeated start-up/shutdown cycles – effect of TEC power 2W vs 1W for 12/9/09**
- **Immediately after start-up, CC temperature dropped due to cold liquid injection, bringing the TM to 312K.**
- **In the next heating cycle, the loop was shut down and re-started. The cold shock was mild and the loop soon reached SS.**

02/03/2010; 253K sink; 350 g mass; Pre-heating CC; TEC set point@313K on the TM - TC33; PID



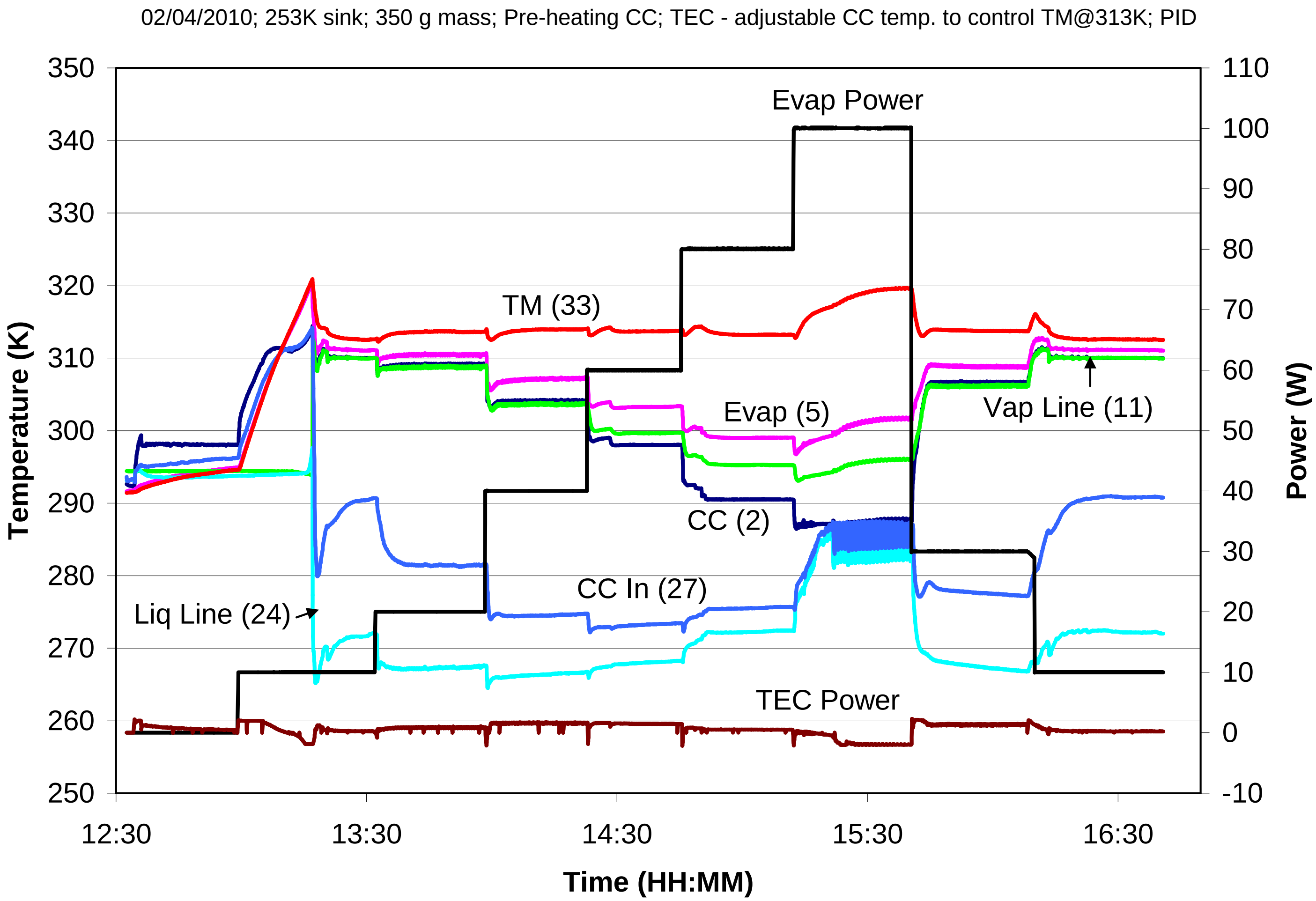
Pre-set CC Temperature Profile to Control TM at 313K (CC Preheated to 298K) – EH/4W/PID/350 g

- The CC temperature was pre-set to previously experimentally determined values (function of power input) in order to keep TM at 313K at all powers.
- The control temperature sensor was located on the CC.
- Temperature oscillations at 10W and 20W, stable 40W to 100W
- Condenser limit was reached at 100W; EH deactivated, and TM at 317K.



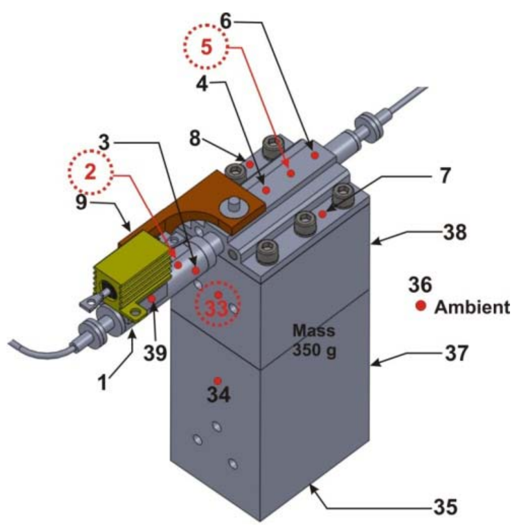
Pre-set CC Temperature Profile to Control TM Controlled 313K – TEC/PID/2W/350g

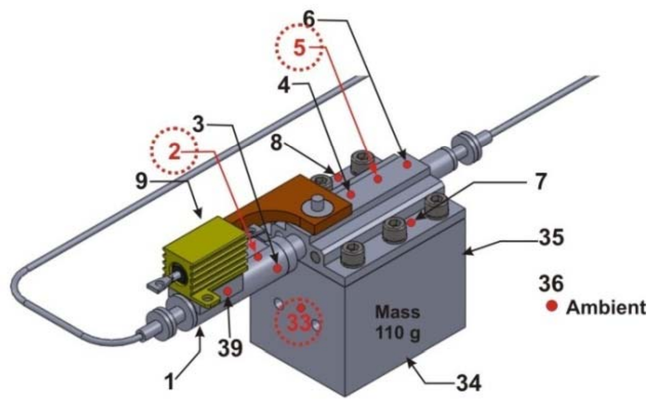
- The CC temperature was pre-set to previously experimentally determined values (function of power input) in order to keep TM at 313K at all powers.
- The control temperature sensor was located on the CC.
- All temperatures were stable. At each power increase, TM temperature dropped because of a step change in the pre-determined CC set point.
- Condenser limit was reached at 100W. CC could not cooled further to maintain the TM at 313K.



Effect of Thermal Mass

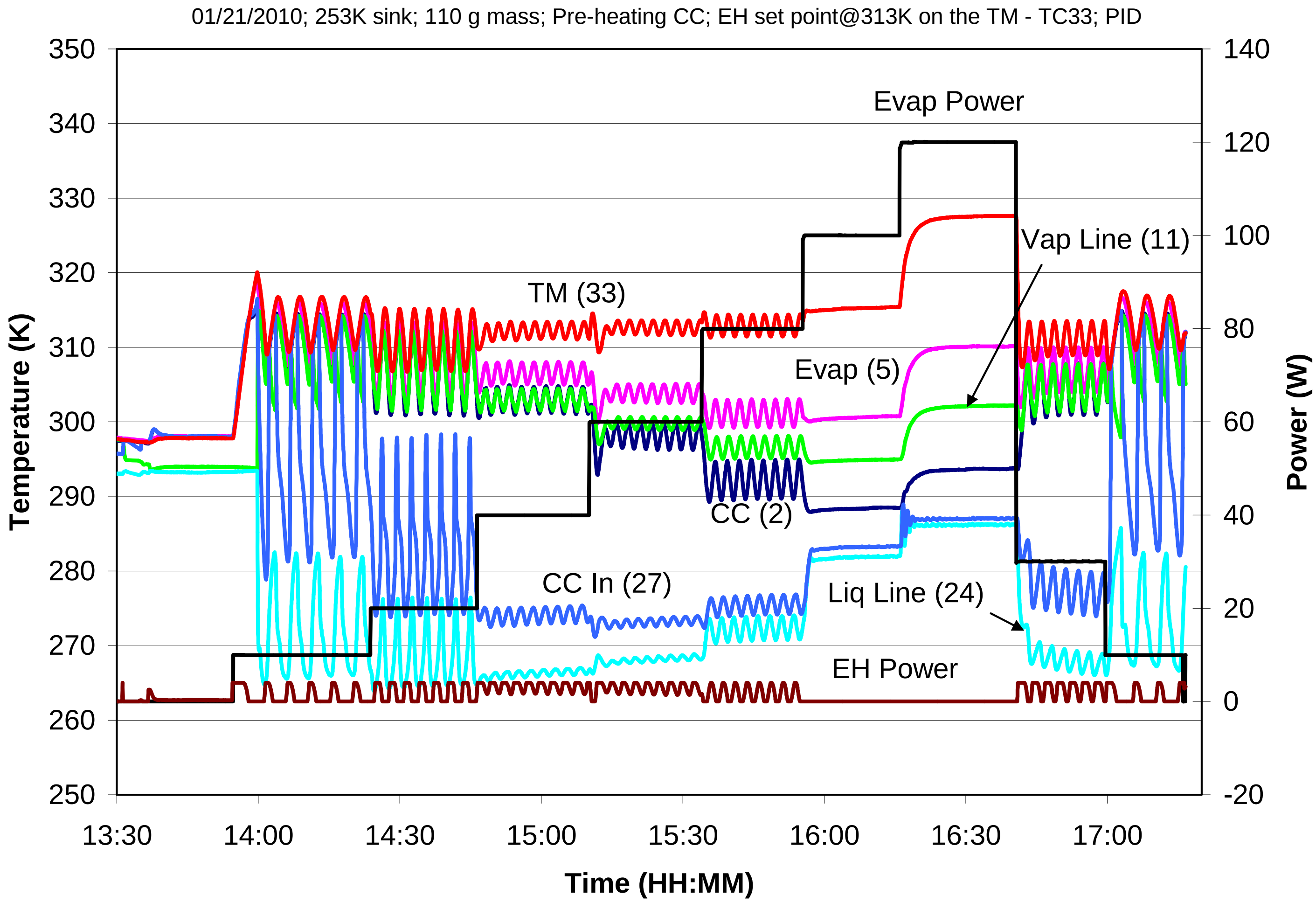
- The following slides show the test result with 110g thermal mass attached to the evaporator.
- In theory, a smaller thermal mass should reduce the time delay in the feedback control when the control temperature sensor is located on the thermal mass.
- Test results under the current test program did not show much thermal mass effect on the LHP temperature control. This may be due to the proximity of the control temperature sensor and the heater locations on the thermal masses.





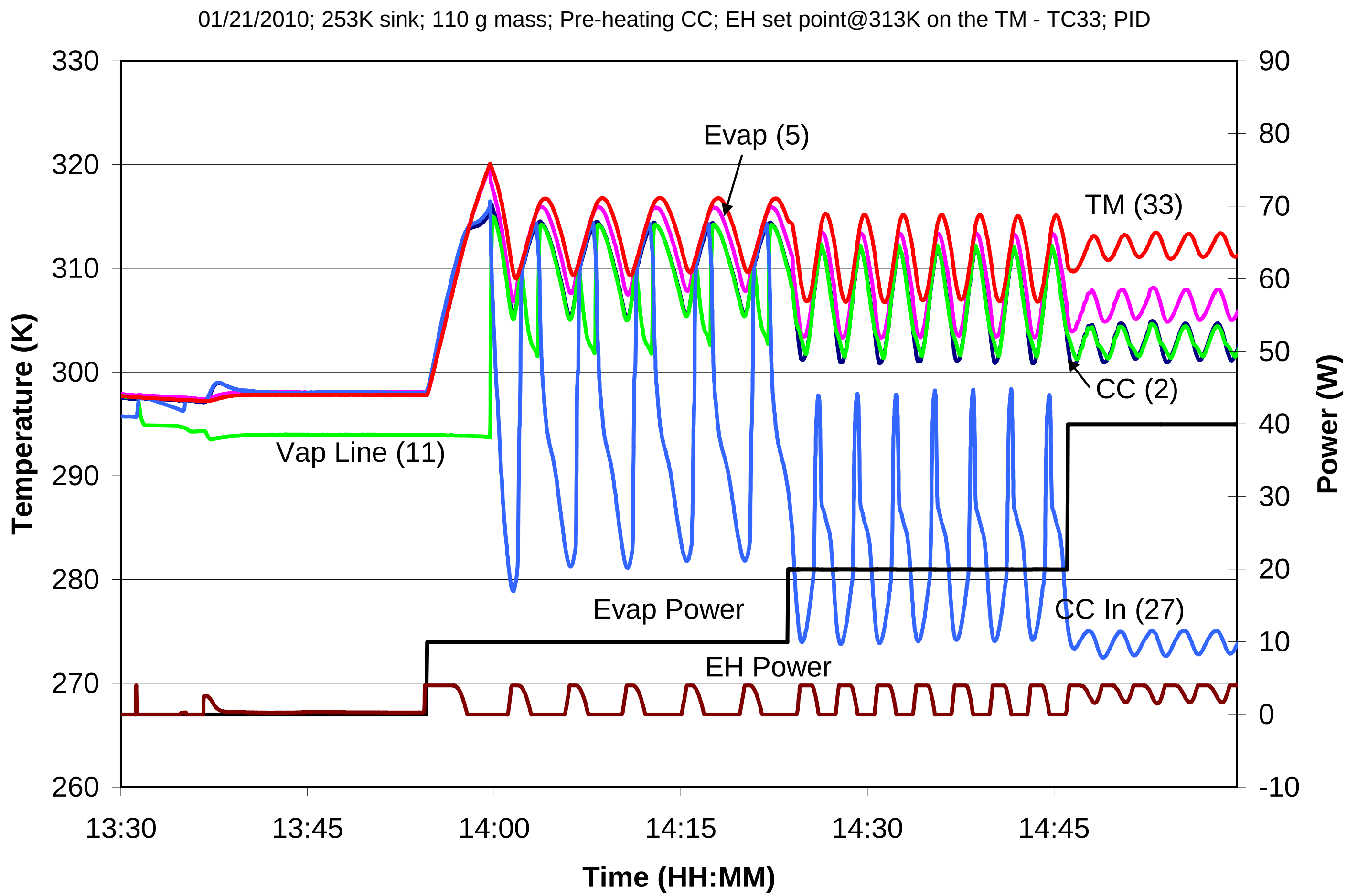
TM Maintained at 313K (CC Preheated to 298K) - EH/4W/PID/110g

- **TM temp was maintained at 313K with oscillations up to 80W.**
- **At 100W, TM temp at 315K due to condenser limit (EH deactivated, no oscillations).**
- **Temp oscillations resumed at 30W and 10W.**



TM Maintained at 313K (CC Preheated to 298K) - EH/4W/PID/110g

- **At 10W, repeated start-up/shutdown cycles even with 110g TM.**
- **At 20W, still large temperature oscillations.**



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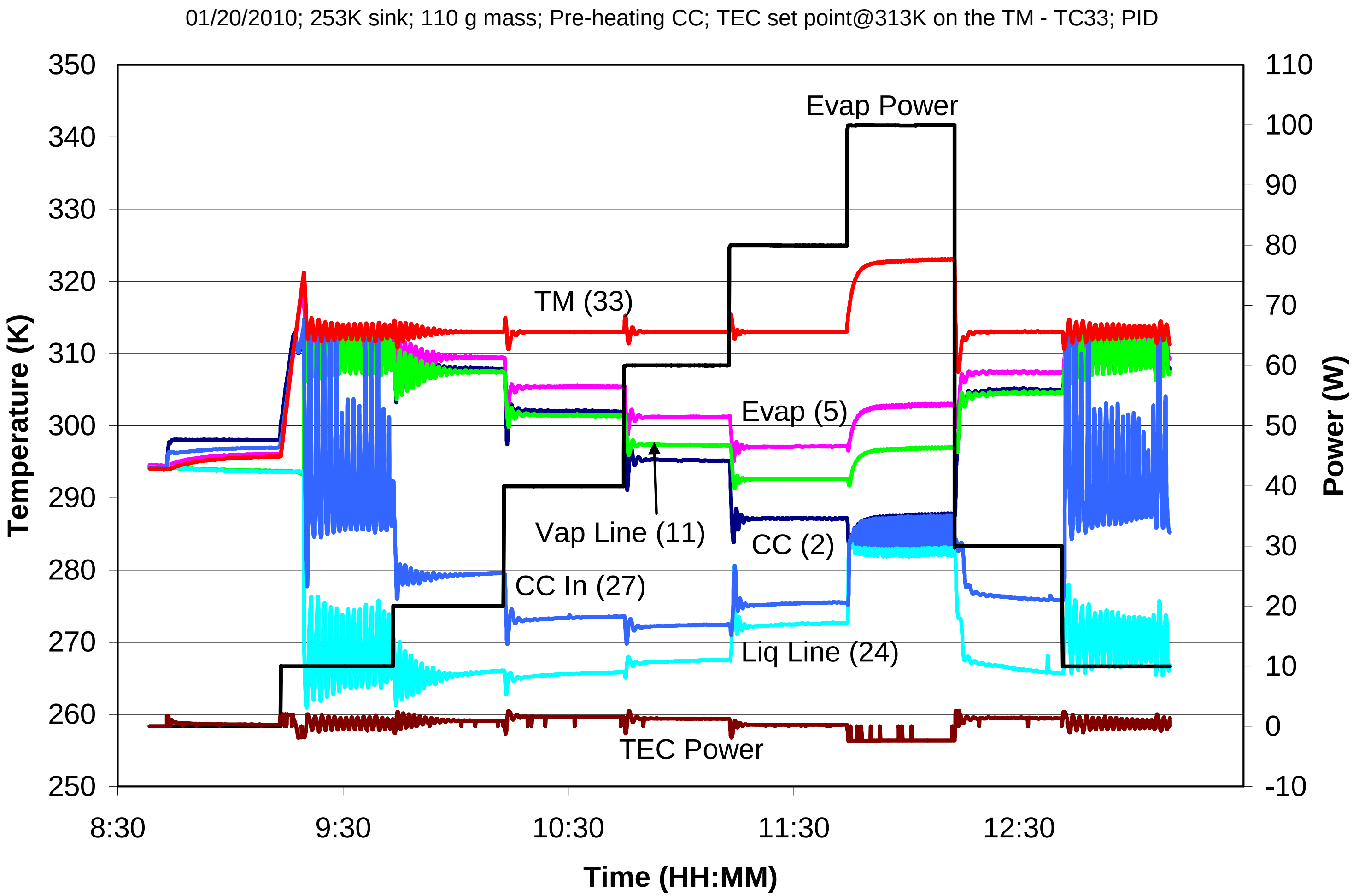
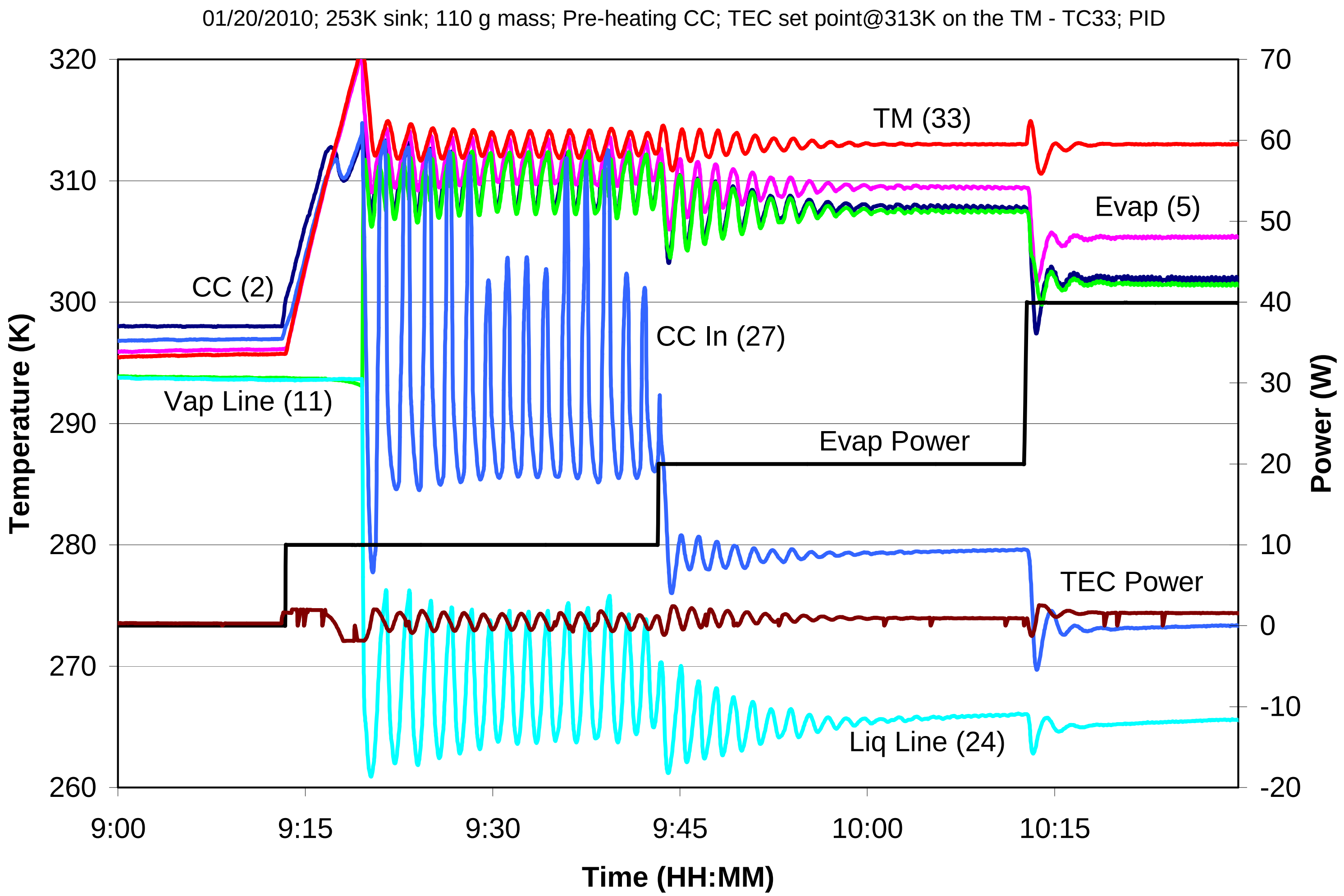
TM Controlled at 313K (CC Pre-Heated to 298K) – TEC/2W/PID/110g

- **TM was controlled at 313K between 20W and 80W**
- **Condenser limit was reached at 100W; TM at 323K**
- **TM was controlled at 313K as heat load decreased to 30W**
- **Temperature oscillations at 10W at the beginning and the end of the test.**



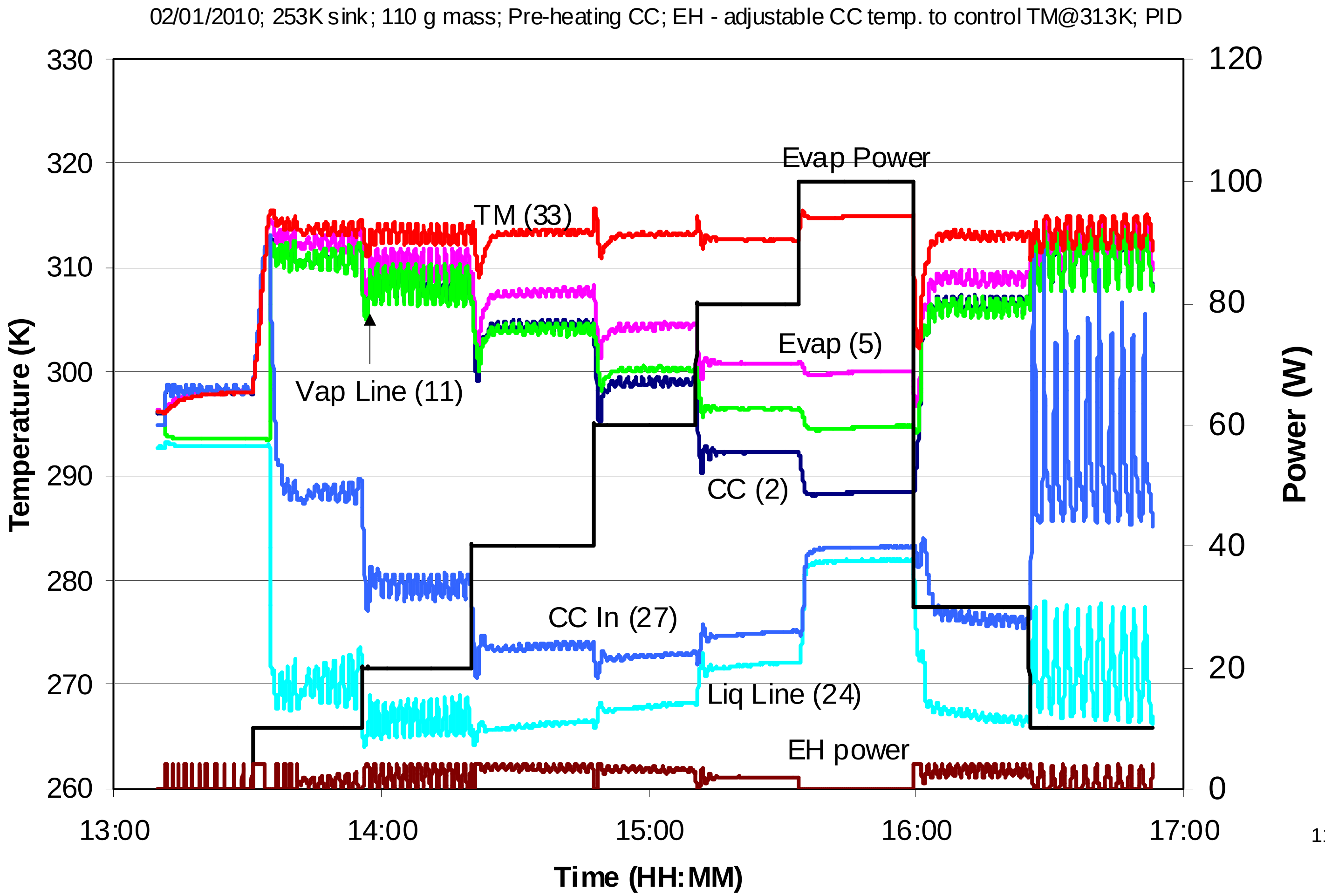
TM Controlled at 313K (CC Pre-Heated to 298K) – TEC/2W/PID/110g

- **TEC 2W max. CC temperature rose faster than that of TM**
- **TEC cooled CC after TM reached 313K, the loop then started. TM oscillated between 312.3K and 313.7K**
- **Repeated start-up/shutdown at 10W**



Using Pre-set CC Set Point to Maintain TM at 313K (CC Pre-Heated to 298K) – EH/4W/PID/110g

- **The CC temperature was pre-set to previously experimentally determined values (function of power input) in order to keep TM at 313K at all powers.**
- **The control temperature sensor was located on the CC.**
- **TM temperature was controlled at 313K between 10W and 80W. Condenser limit was reached at 100W.**
- **At each CC set point change, TM could not follow immediately, resulting in TM temperature fluctuations.**



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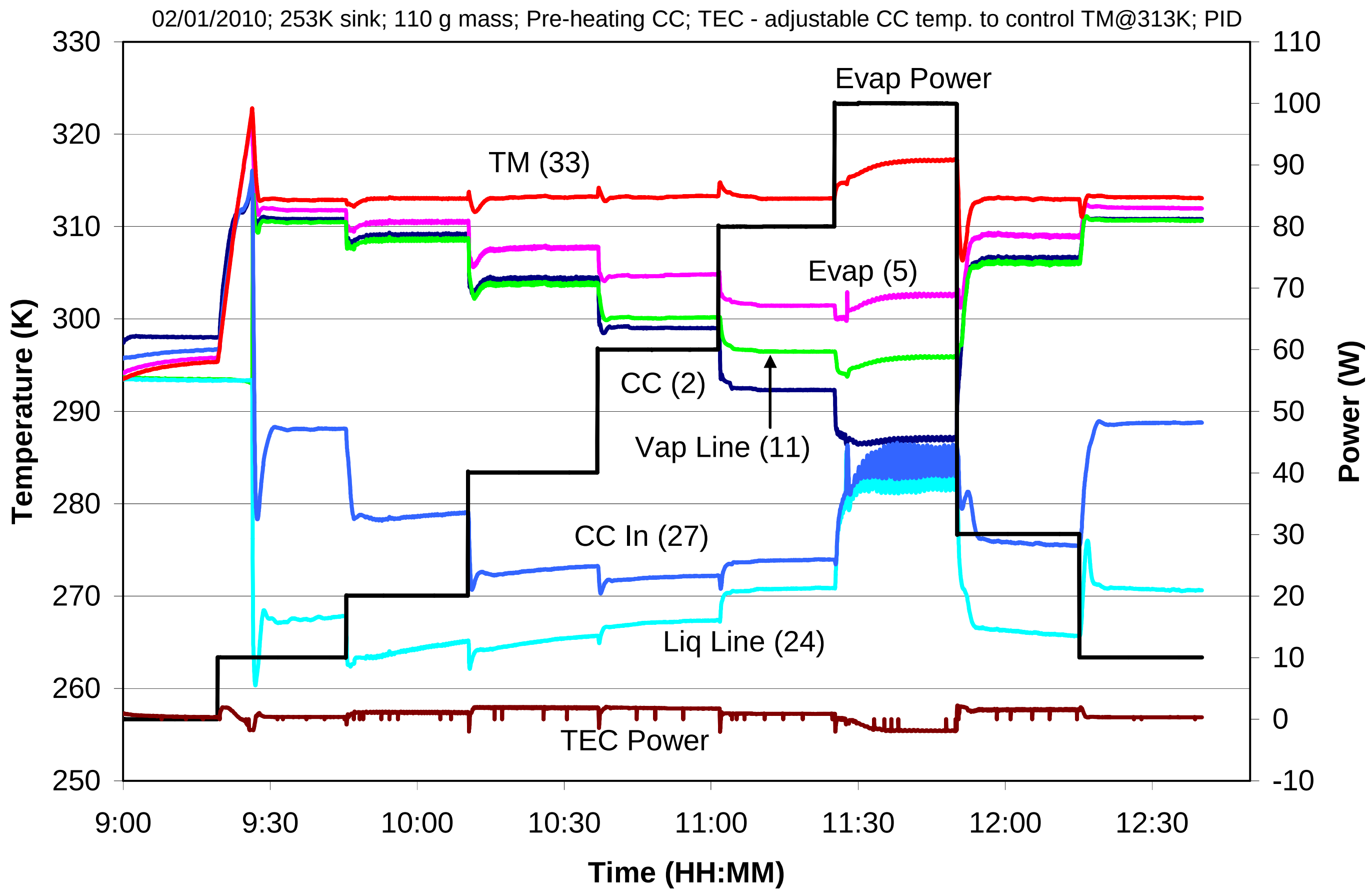
Using Pre-set CC Set Point to Maintain TM at 313K (CC Pre-Heated to 298K) – TEC/2W/PID/110g

- **The CC temperature was pre-set to previously experimentally determined values (function of power input) in order to keep TM at 313K at all powers.**
- **The temperature sensor was located on the CC.**
- **TM temperature was controlled at 313K between 10W and 80W. Condenser limit was reached at 100W.**
- **TM temperature oscillated at 10W and 20W.**



Summary of Test Results

- The LHP CC temperature or the heat source temperature can be used for LHP set point control with a control heater attached to the CC.
- The traditional method of using CC temperature for LHP set point control yields best temperature stability.
  - However, the heat source temperature will vary with the heat output from the heat source.
- Using the heat source temperature as feedback for LHP set point control will maintain the heat source at the desired temperature regardless of the heat output.
  - However, temperature oscillations may appear during transients and can be severe at low heat loads.
- Using a TEC to control the CC temperature yields better temperature stability than using an electric heater.
  - The control heater power also affects the temperature stability.

Concluding Remarks

- There are many factors to be considered in deciding which temperature should be used for LHP feedback control.
- For most applications, using the CC temperature for feedback control is preferred as long as the heat source can be maintained within the required temperature range.
  - A simple control algorithm will suffice for SS and transients.
  - The CC set point can be varied while the LHP is operating in space.
- The heat source temperature can best be used for feedback control for applications where the heat load varies constantly without frequent LHP start-ups and shut-downs.
  - The heat source can be maintained within a tight temperature range through automatic adjustments of the CC temperature.
- More sophisticated (smart) control algorithms must be employed when frequent start-ups or rapid power changes are involved if the heat source temperature is to be used for feedback control.

QUESTIONS?