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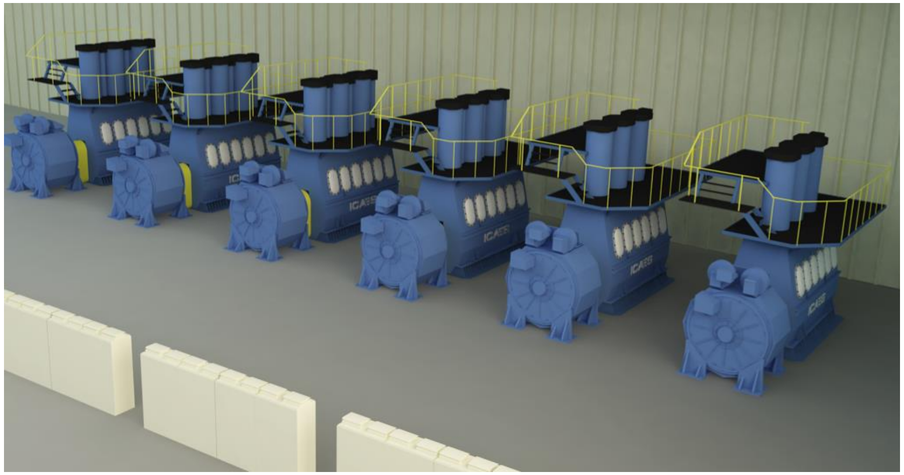
Sunapee Polytropic Index Analysis
8 July 2014



Polytropic Index

- Polytropic Index is an overall measure of thermodynamic & heat transfer effectiveness
  - Indicates both the water:air mass ratio and in-cylinder foam quality (but cannot necessarily differentiate between them)

- Polytropic Index relates a gas's state properties (P, T, and V) during a thermodynamic process (e.g. compression or expansion)
  - PV^n = constant (useful for cylinder analysis)
  - $P^{(1-n)}T^n$ = constant (useful for LP & HP stage analysis)

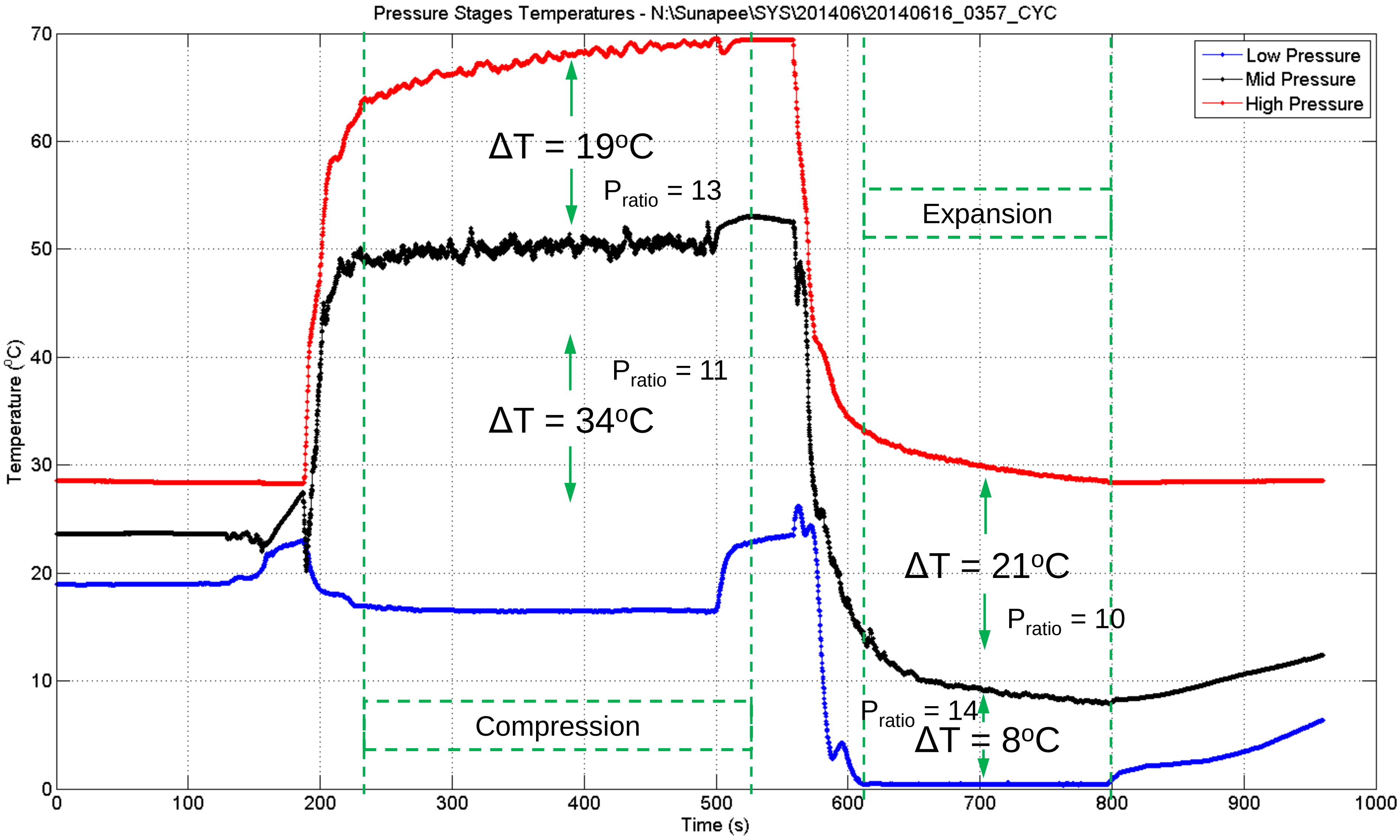
$$n = \frac{\ln P_1 - \ln P_2}{(\ln T_2 - \ln P_2) - (\ln T_1 - \ln P_1)}$$

    - LP Stage: 1=LPM, 2=MPV
    - HP Stage: 1=MPV, 2=HPM

  - n = 1 is isothermal; n = 1.4 is adiabatic

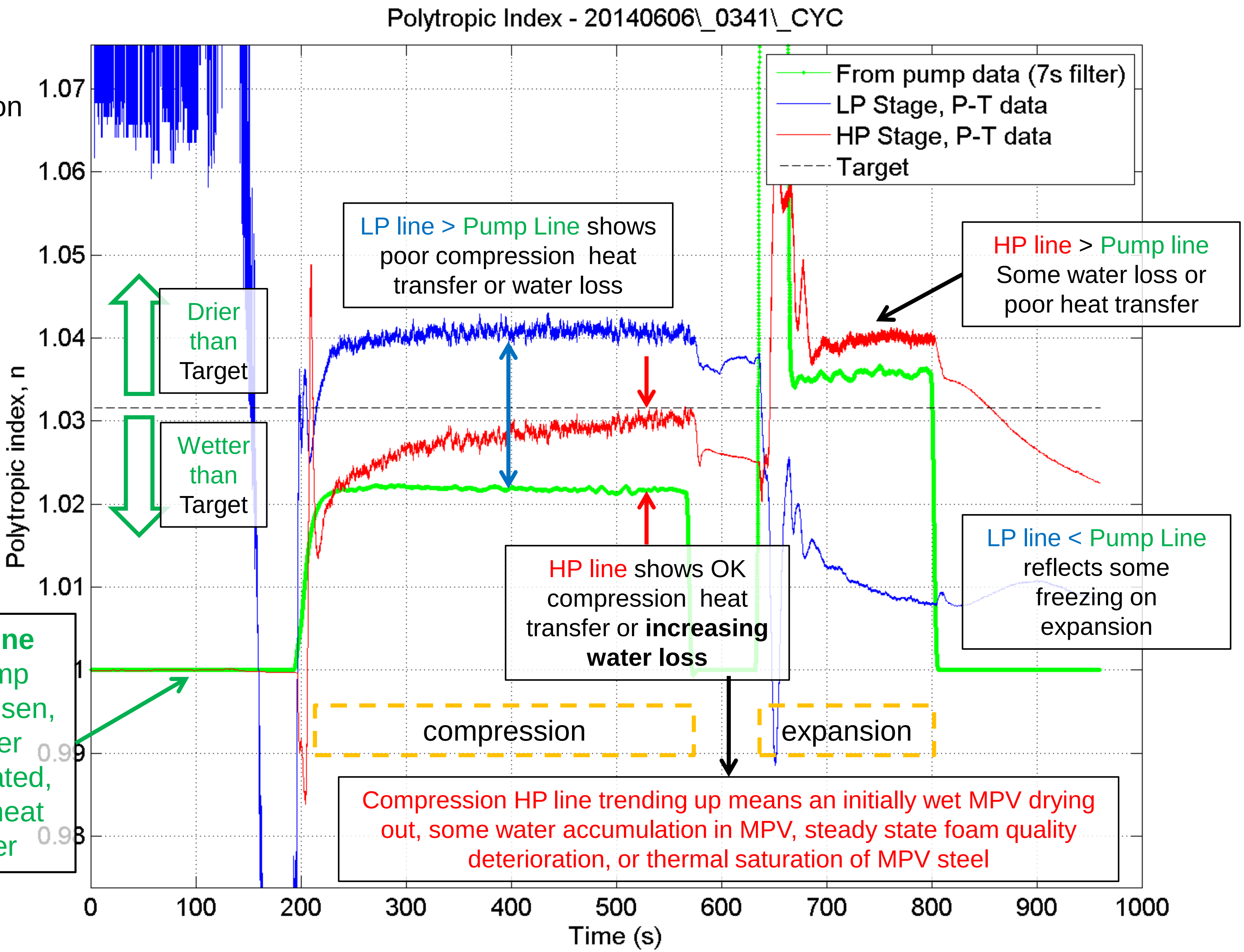
- For a mass ratio of 2:1 water:air, i.e. air mass fraction = 1/3,
  - n = 1.032, given that *heat transfer >> thermodynamic process*

Pressure Stages Temperatures



Polytropic Index Graph – LP Single Screen

21 bar compression
14 bar expansion

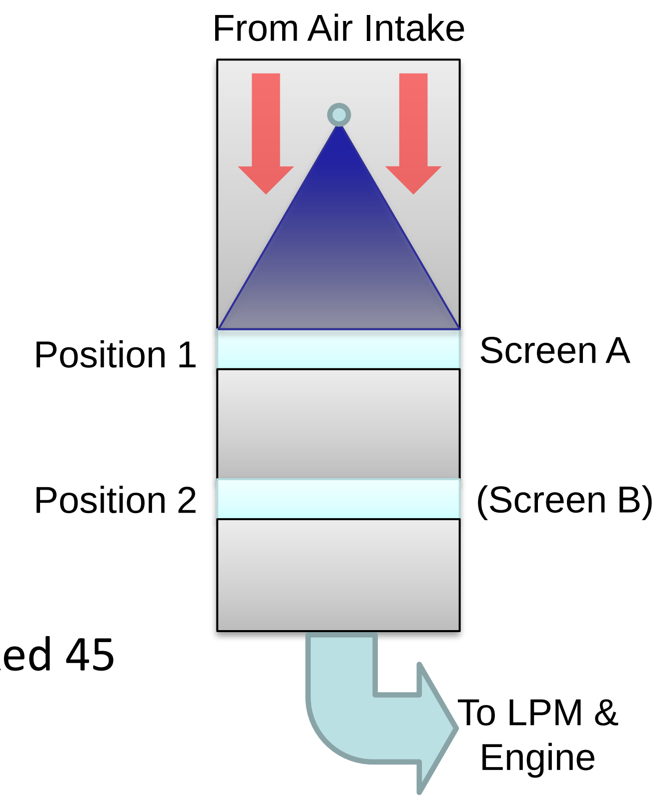


Ideal Line for pump flows chosen, all water incorporated, perfect heat transfer

Compression HP line trending up means an initially wet MPV drying out, some water accumulation in MPV, steady state foam quality deterioration, or thermal saturation of MPV steel

LP Foam Generation

- Single Screen experiments
  - Screen A
  - ~April 1st 2014 to June 6th 2014
  - Experiment ~# - #342
- Double Screen experiments
  - Screen A+B
  - June 10th to present
  - Experiment ~#343 – Latest (#372)



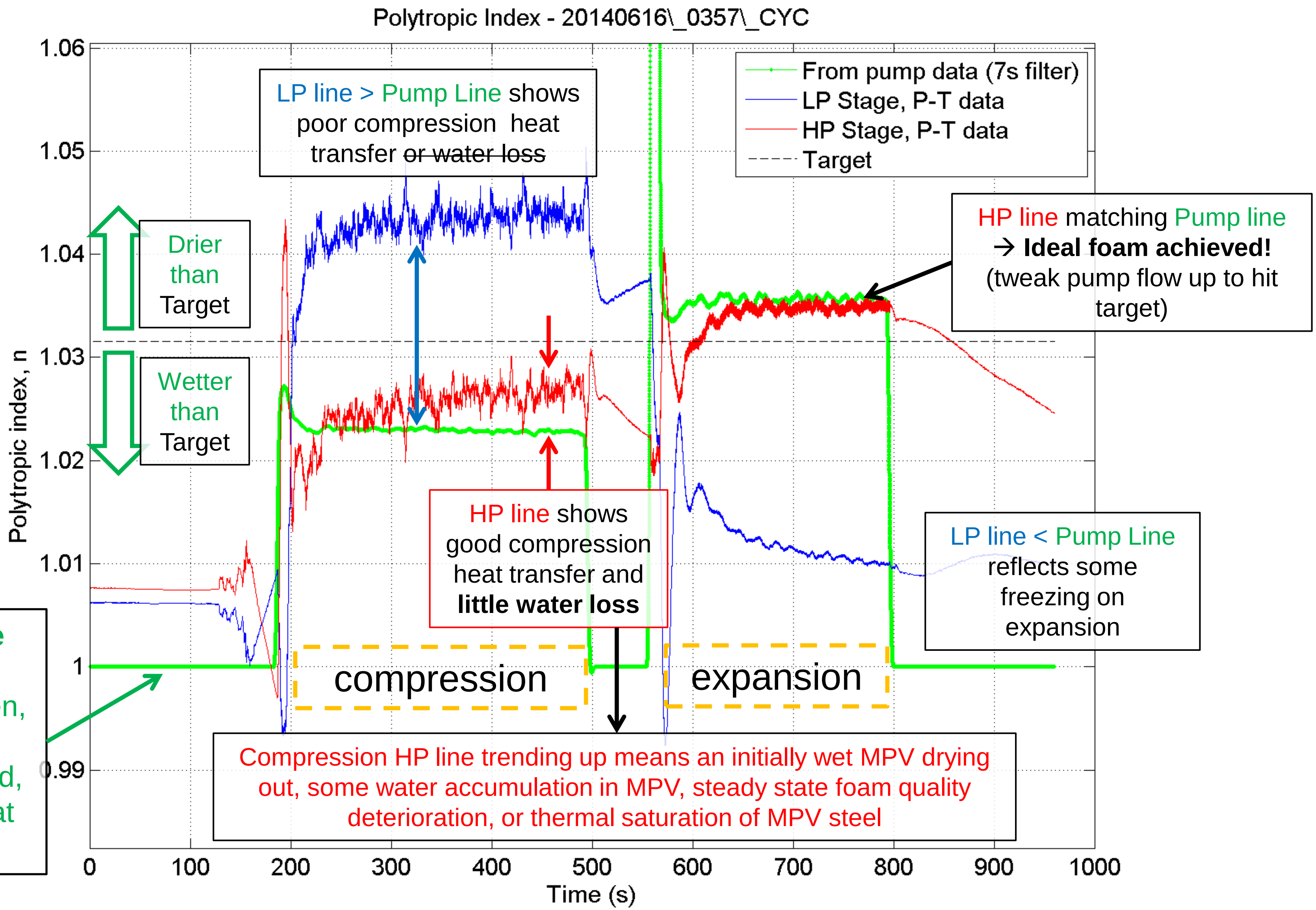
- Screen B – **ideal screen**
  - 3 layer (Coarse-medium-fine) square meshes, clocked 45 degrees to one another
- Screen A – manufacturer's mistake
  - 6 layer (C-M-F-F-M-C) square meshes, no clocking pattern/random clocking to one another

Note:

- All water for LP & HP compressions comes from LP foam
- All water for LP & HP expansions comes from HP foam

Polytropic Index Graph – LP Double Screen

18 bar compression
18 bar expansion



Ideal Line for pump flows chosen, all water incorporated, perfect heat transfer

Results

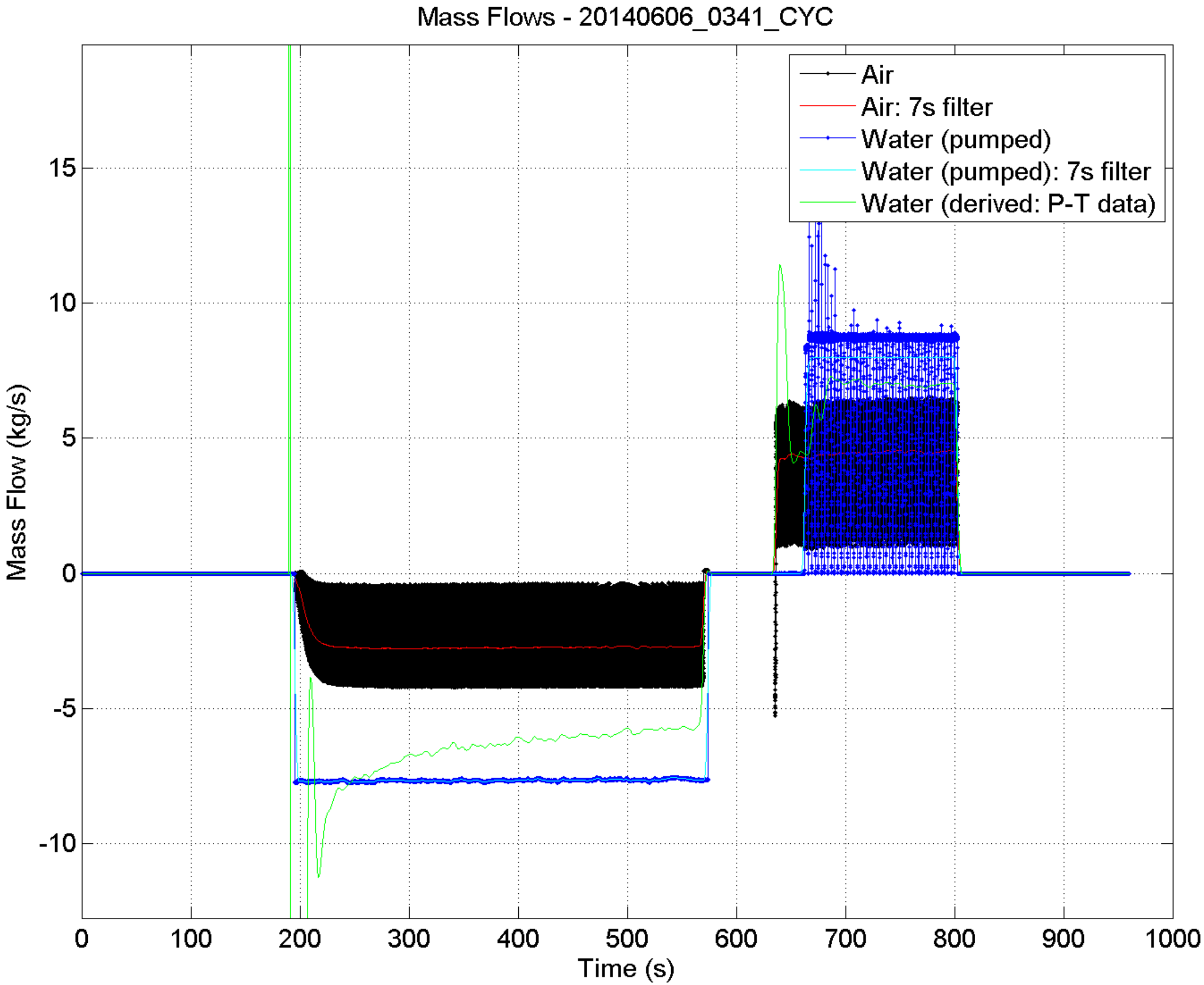
- Compressions & LP Foam
  - LP stage polytropic index is consistently higher than ideal or the HP stage; nearly constant, very little trending
  - HP stage polytropic index starts near ideal then trends up
  - Single vs. Double Screen
    - Single screen has faster upward trend for HP stage (qualitatively)
- Expansions & HP Foam
  - HP stage close to ideal
  - LP stage partially freezing

Discussion

- Compressions Foam: HP stage ~= ideal
  - → the water is getting into the system (and passing through the LP stage)
    - → the LP stage is dominated by poor heat transfer, not incorrect mass ratio
- Compressions Foam: HP stage trending up (drier)
  - Water does not enter system i.e. drains out in LPM
  - Water falls out of foam in MPV, accumulates in MPV
  - MPV foam starts out wet, dries out during steady state operation
  - Foam quality deteriorates during steady state operation
  - Heating up of the HPM steel
    - Analysis is based on manifold temperatures – cold steel could artificially lower the manifold's temperature initially

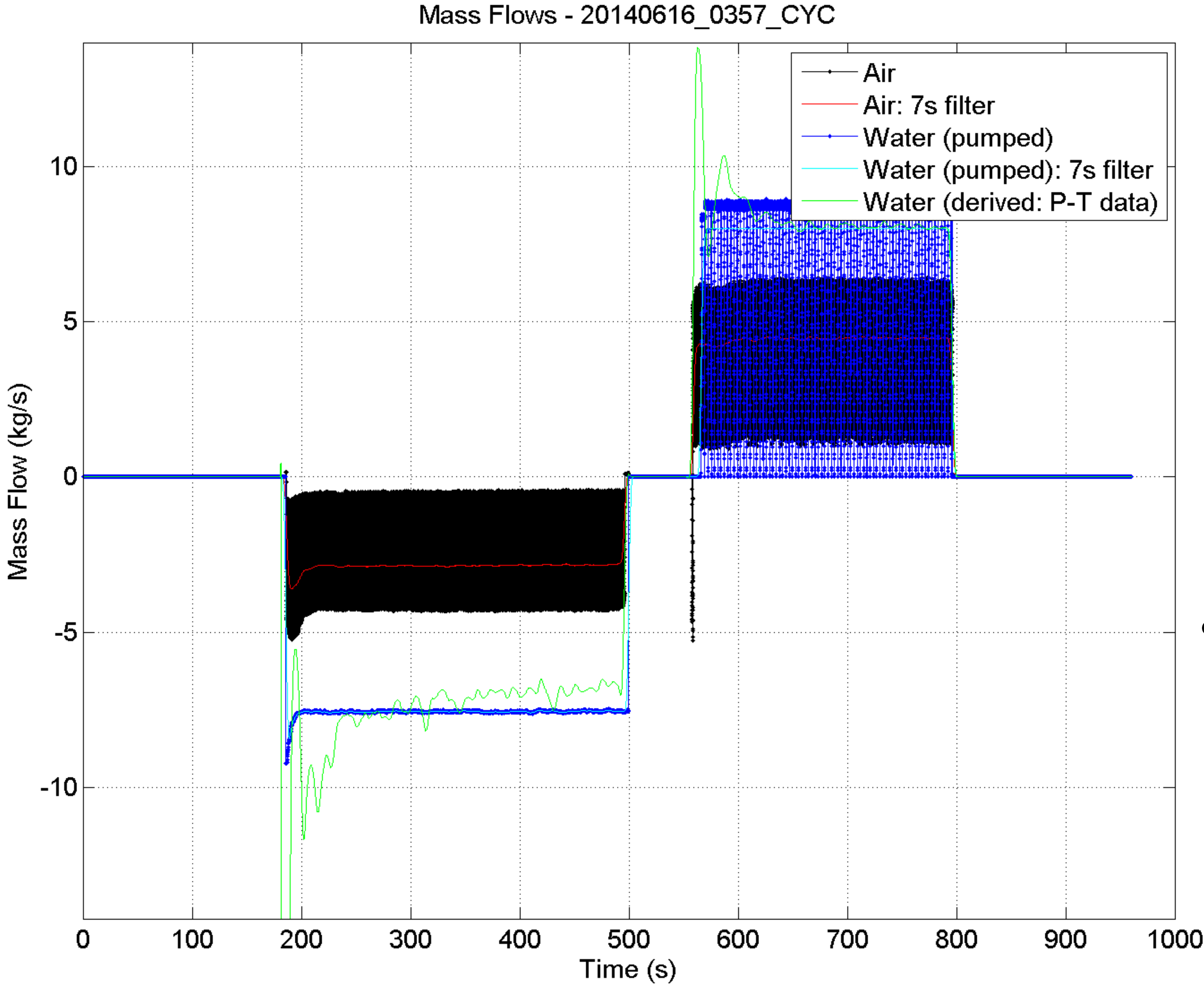
- Can freezing be exploited by design?
  - Low exhaust vapor losses as well
- Could boiling be exploited by design?
  - Phase changes represent near-perfect thermal processes
  - kJ Per kg water: 2260 (boiling) > 334 (freezing) > 105 (4.2x25 K, heat capacity)

Mass Flows Graph – LP Single Screen



- Assuming polytropic index trending is due to lost water

Mass Flow Graph – LP Double Screen



- Assuming polytropic index trending is due to lost water

Current Limitations

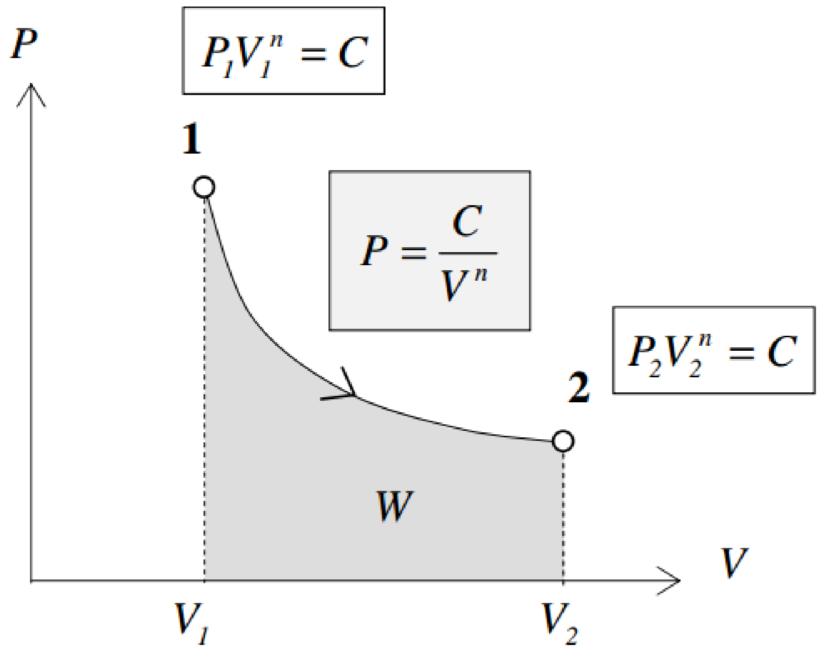
- Double screens have increased LPM pressure drops, increasing the foam starvation of LPC-540 → LPC-540 compression exhaust temperatures ~90oC at "too wet" LP foam levels
  - Cannot bring LP water flow down to match target without exceeding 93oC (start of steel de-rating)
- Expansions should run slightly wetter → potential additional foam separation difficulties
- Expansions need warmer storage such that there's no freezing in the LP stage → LP expansions foam quality can then be quantified

Future Work

- Analysis
  - Polytropic analysis for Spray Ring experiments
  - Analyze warm STG, non-freezing exhaust experiments
  - Per cylinder polytropic indices
  - MPV Gas Volume Fraction → try to deduce if water is accumulating
  - Lost work due to not achieving ideal foam & target index
    - Work (see next slide)
    - Efficiency, heat transfer
  - Automatic analysis for each experiment
    - Average polytropic index (and rate of change), estimated water loss, work
- Measurement
  - MPV & HPM skin temps – thermal gun after long runs, or surface thermocouples
- Controls
  - Reduce HP foam mass ratio transients through better closed-loop control
    - Use feed-back from HPCs foam sensors
    - (Feed-forward from STG foam sensor)
- Tests
  - Turn on MPV refoaming pumps & run long cycle(s)
  - Screen B only
  - Switch screens
  - Remove MPV screen to see its effect on refoaming

- LP Manifold redesign for even foam distribution

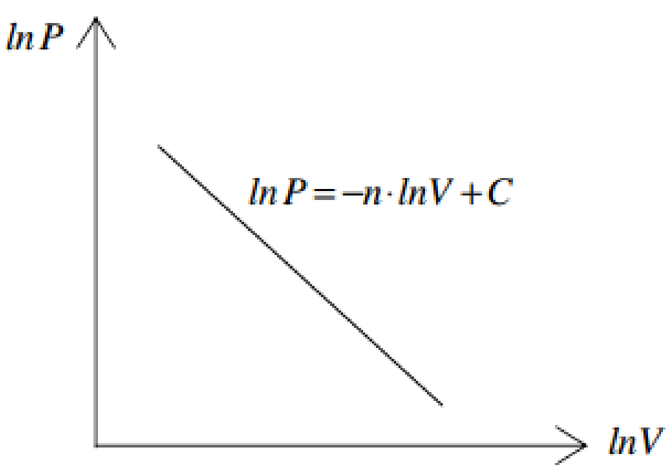
Polytropic Processes of Gases



n, C are constants

$$PV^n = C$$

$$P_1V_1^n = P_2V_2^n$$



$n = 0 \Rightarrow P = const$ isobaric

$n = 1 \Rightarrow T = const$ isothermal (ideal gas)

$n = k \Rightarrow s = const$ isentropic

$n = \infty \Rightarrow v = const$ isochoric

Polytropic Process Work

$(n \neq 1)$:

$$W = \int_1^2 P dV = C \int_1^2 V^{-n} dV$$

$$= \frac{1}{1-n}\left(C V_2^{1-n} - C V_1^{1-n} \right) \quad \Leftarrow \quad \boxed{C = P_1 V_1^n = P_2 V_2^n}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Ideal gas:

$$PV = mRT$$

$$P_1 V_1 = mRT_1$$

$$P_2 V_2 = mRT_2$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{1-\frac{1}{n}} = \left(\frac{V_1}{V_2} \right)^{n-1}$$

$$W = \frac{mR}{1-n}\left(T_2 - T_1 \right)$$