A Hardware-Based Modeling and Design Tool for Heat Pump Water Heaters –ORNL Heat Pump Design Model

Bo Shen, Kashif Nawaz,
Ahmed Elatar, Van Baxter

Building Technologies Research and
Integration Center, ORNL

shenb@ornl.gov

ACEEE Hot Water Forum 2017

OAK RIDGE
National Laboratory

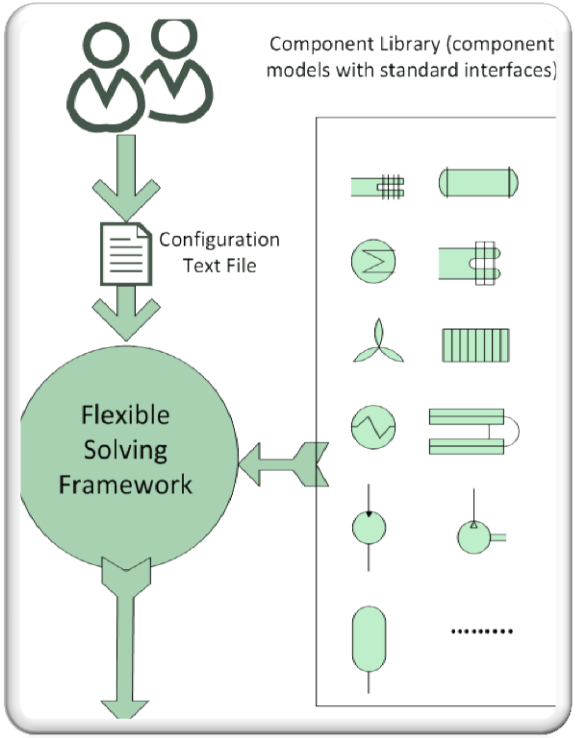
Content

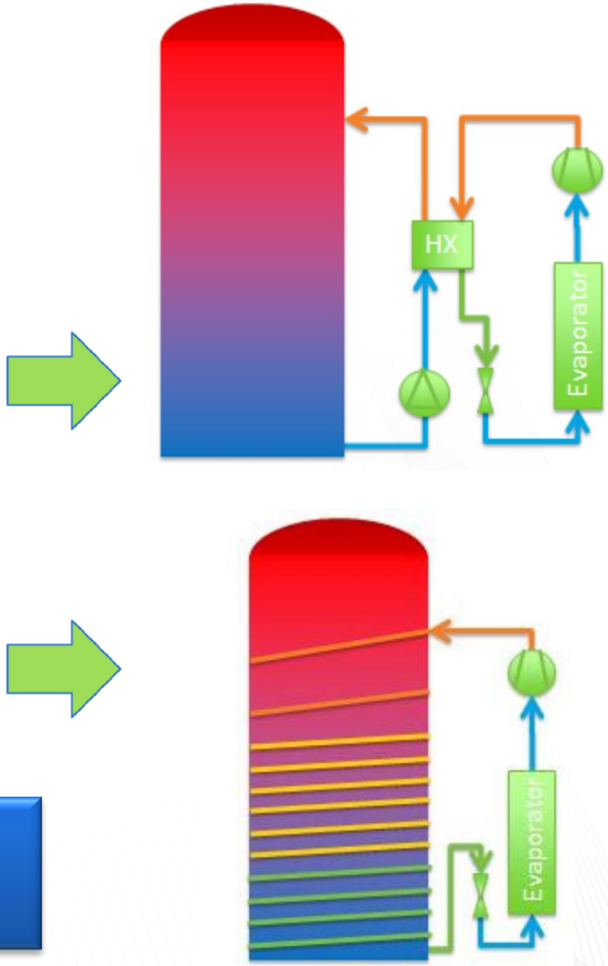
1. Introduction of ORNL Heat Pump Design Model (HPDM)
2. Improved EnergyPlus stratified water tank model
3. Segment-by-segment wrapped-tank coil model
4. Design case study
5. Summary

1. ORNL HPDM - Component-Based Flexible Modeling Platform for Vapor Compression Systems

Component-Based

Component models have standard interfaces to the solving framework, and generic connections to each other.





Automatically connect components into required system configuration by user input file.

Search website using Google “ORNL HPDM”

1. Compressor Modeling

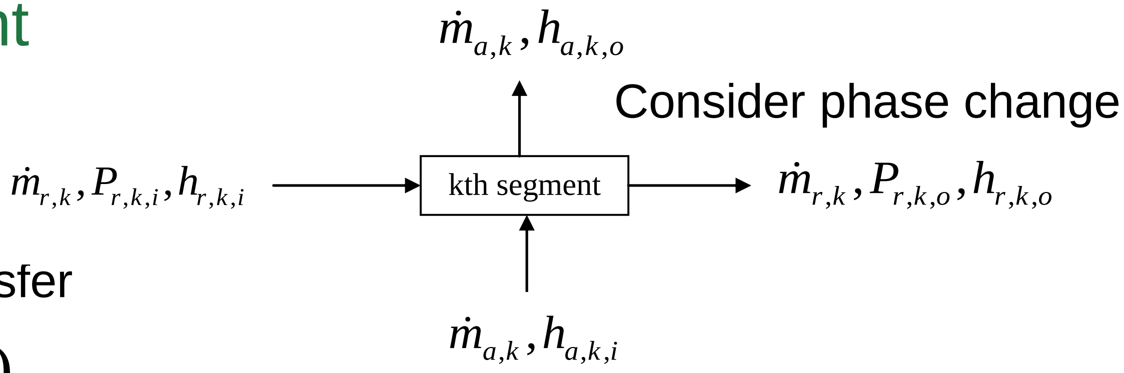
$$Y = C_1 + C_2 T_e + C_3 T_c + C_4 T_e^{2} + C_5 T_e T_c + C_6 T_c^{2} + C_7 T_e^{3} + C_8 T_c T_e^{2} + C_9 T_e T_c^{2} + C_{10} T_c^{3}$$

- 10-coefficient AHRI compressor map at rated inlet superheat; Y is the compressor mass flow rate or power consumption.
  - Linear interpolation between speed levels to model a variable-speed compressor.
  - Mass flow rate adjustment for actual inlet superheat levels.

- Or basic efficiency compressor model: requires compressor displacement volume, rotational speed, volumetric and isentropic efficiencies
- Other compressor models to be added as needed.

1. Advanced Heat Exchanger Modeling

- Segment-to-segment modeling approach



$\dot{m}_{a,k}, h_{a,k,o}$

Consider phase change

$\dot{m}_{r,k}, P_{r,k,i}, h_{r,k,i}$

kth segment

$\dot{m}_{r,k}, P_{r,k,o}, h_{r,k,o}$

$\dot{m}_{a,k}, h_{a,k,i}$

Dry Coil Analysis Heat Transfer

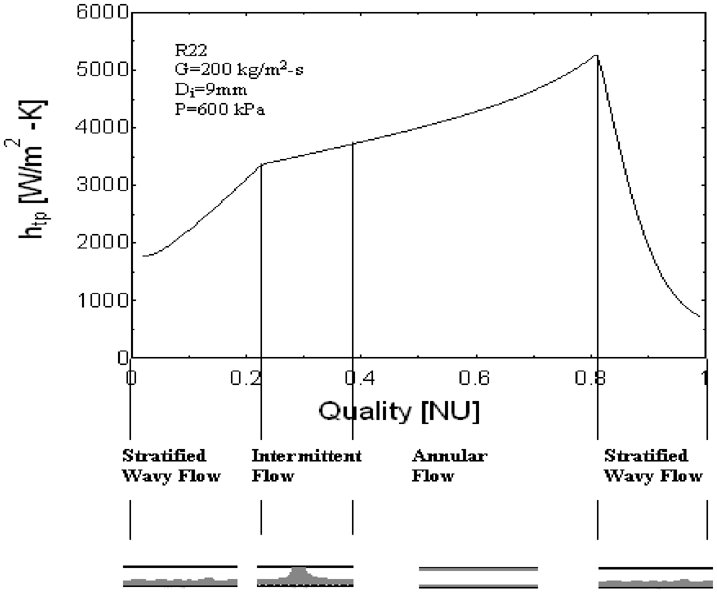
$$\dot{Q}_{\max} = C_{\min}(T_{h,i} - T_{c,i})$$

$$\varepsilon = 1 - \exp(-NTU)$$

Wet Coil Analysis Heat & Mass Transfer

$$\dot{Q}_{\max} = \dot{m}_a(h_{a,i} - h_{s,evap})$$

$$\varepsilon^* = 1 - \exp(-NTU^*)$$



Refrigerant side local flow-pattern-specific heat transfer and pressure drop calculation

1. Water Heaters

-Segment-to-segment modeling approach

Brazed Plate HX

-Heat transfer and pressure drop correlations obtained from manufacturer's product selection tool.

Tube-in-Tube HX

Correlation: Rousseau, P.G., Eldik, M.V., and Greyvenstein, G. P., 2003. "Detailed simulation of fluted tube water heating condensers." International Journal of Refrigeration 26:232–9.

First-principle heat exchanger models, work for both subcritical refrigerants (R-134a,etc) and supercritical refrigerant (CO2)

2. Stratified Water Tank Model

Start with EnergyPlus stratified tank model

- What the EnergyPlus stratified tank model provides:

→A transient tank model

→accounts for one-dimensional water temperature stratification, up to 10 nodes

→simulates supplemental heaters, accounts for locations and energy use.

→describes tank heat loss

→describes 1-dimensional piston flow, i.e. water draw

→describes water side heat conduction between nodes

→describes natural convection upward flow and mixing

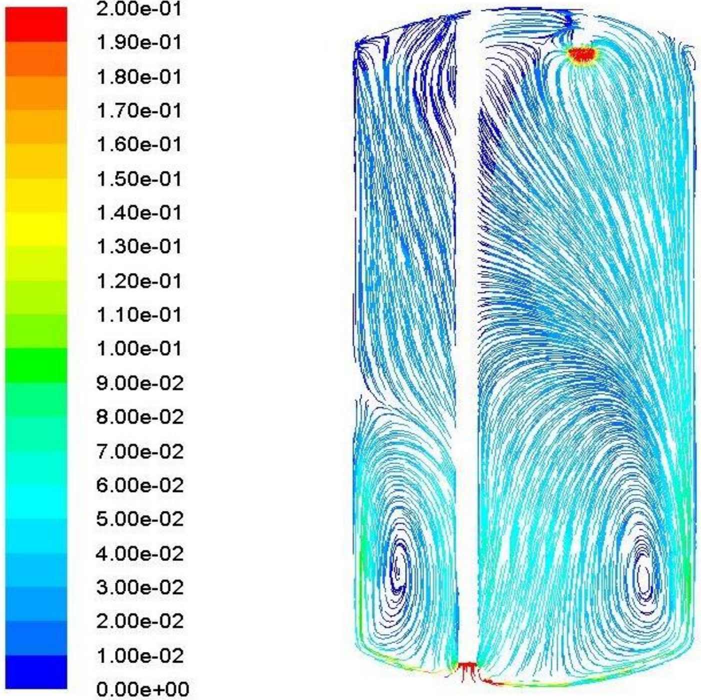
2. Missing Mechanism in E+ Tank Model

What is missing:

→tends to overestimate stratification, why? – missing bulk mixing mechanism during large water draws.

Large water draws introduce whirls, i.e. bulk mixing effect, significant with large water flows, like 3 GPM.

Supply water



Make up water

2. Calibration Method

- Introduce an empirical bulk mixing term – a calibration factor

Energy transfer rate between tank average and nodal temperatures caused by whirls :

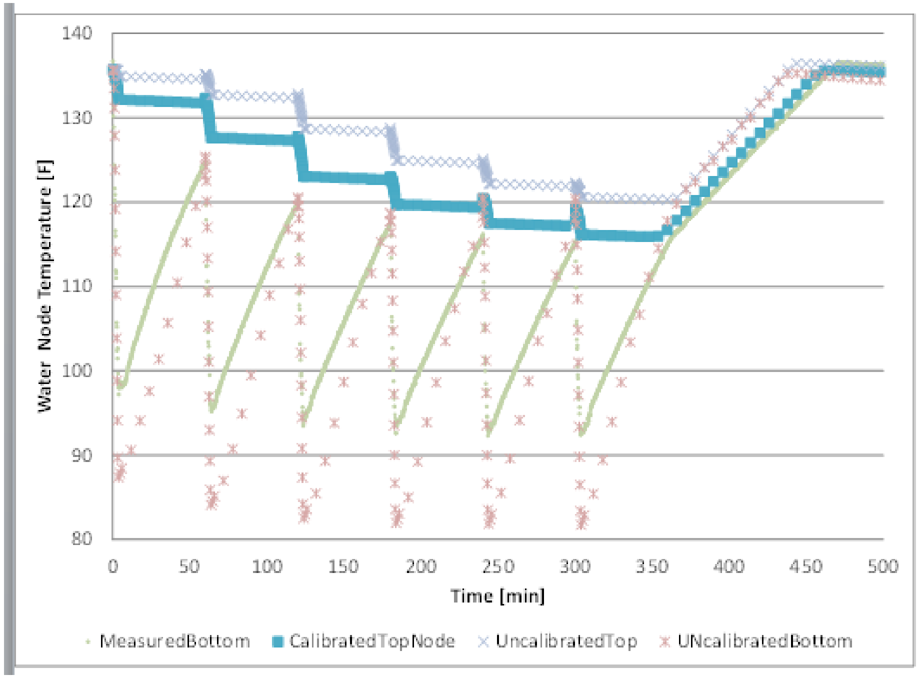
QbulkMix,Node = ***Tank.BulkMixRatio*** * (Ttank,avg - NodeTemp) * NodeMass * Cp

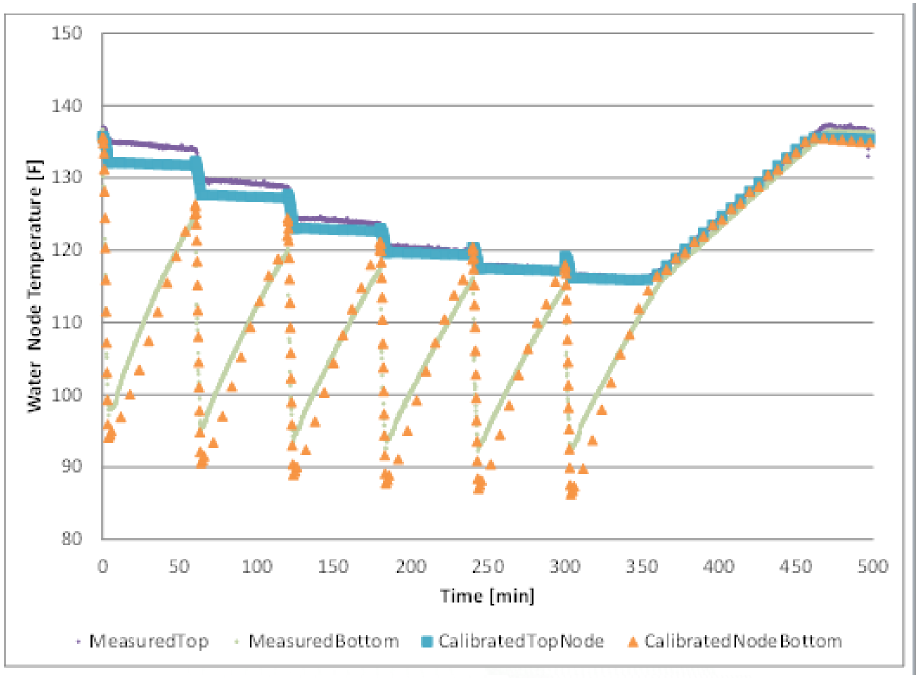
Where:

- Tank.BulkMixRatio (percentage of NodeMass exchanging energy with the bulk flow) is an empirical factor to correlate the mixing effect, can be obtained from calibration against measured data or CFD simulation.
- Tank.BulkMixRatio should be different value with/without water draw
- Ttank,avg is the tank average water temperature at each time step
- NodeTemp and NodeMass are temperature and mass of nodes at each time step
- QbulkMix,Node is the energy transfer to each node, caused by the bulk mixing effect, i.e. whirls

2. Calibrate bulk mixing term against measured water temperature profile

- Matching the measured water stratification profile





-Uncalibrated tank model

-Calibrated tank model

Reasonable calibration factor: 0.15% tank water mass mixed during water draw; Zero bulk mixing when no draw

3. Wrapped-Tank Coil Model

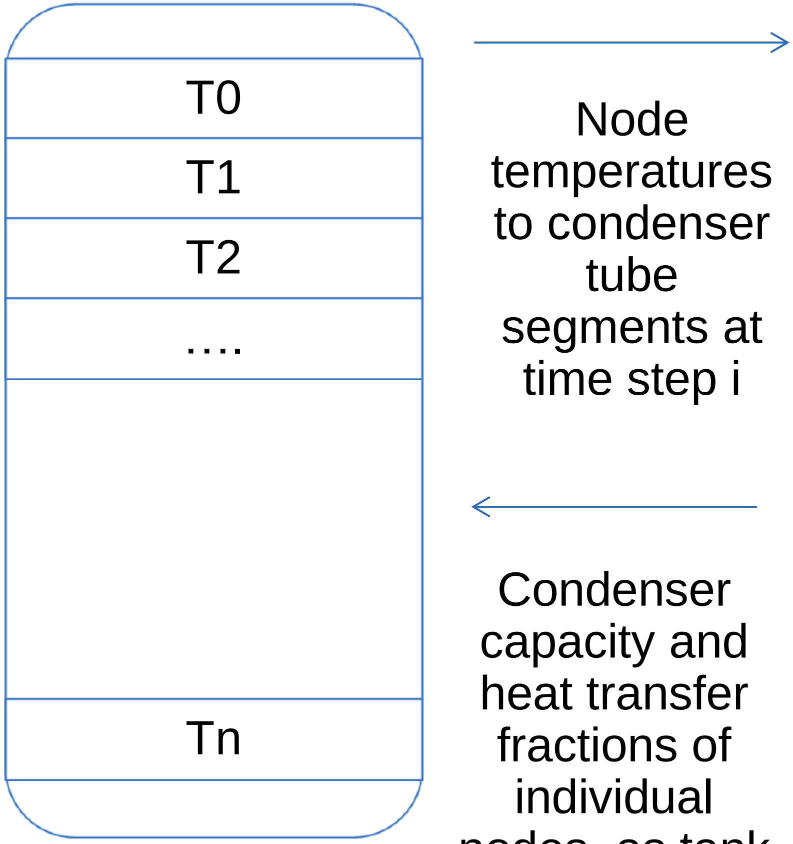
Another missing part: EnergyPlus wrapped-tank coil inputs constant fractions of condenser heat to nodes - never true, since the coil heat transfer is interconnected to the tank temperature distribution.

→Instead we coupled a segment-to-segment coil model to stratified tank model

- Pattern of wrapped-tank coil affects stratification
- Water stratification is a boundary condition to the segment-to-segment coil model

3. Heat Exchange between Tank and Coil

- Quasi-steady-state boundary condition exchange



T0

T1

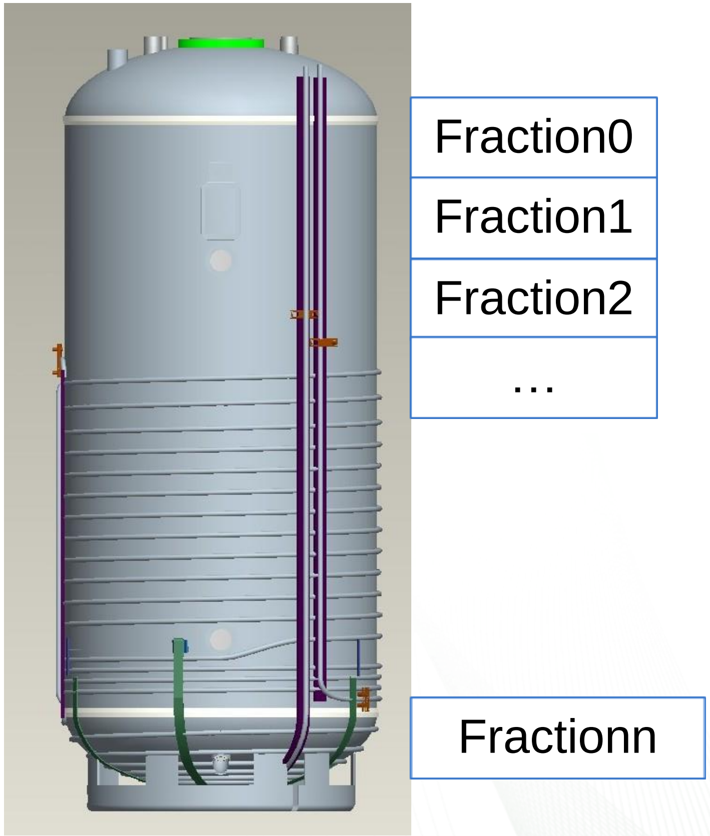
T2

….

Tn

Node temperatures to condenser tube segments at time step i

Condenser capacity and heat transfer fractions of individual nodes, as tank heat transfer inputs at time step i+1



Fraction0

Fraction1

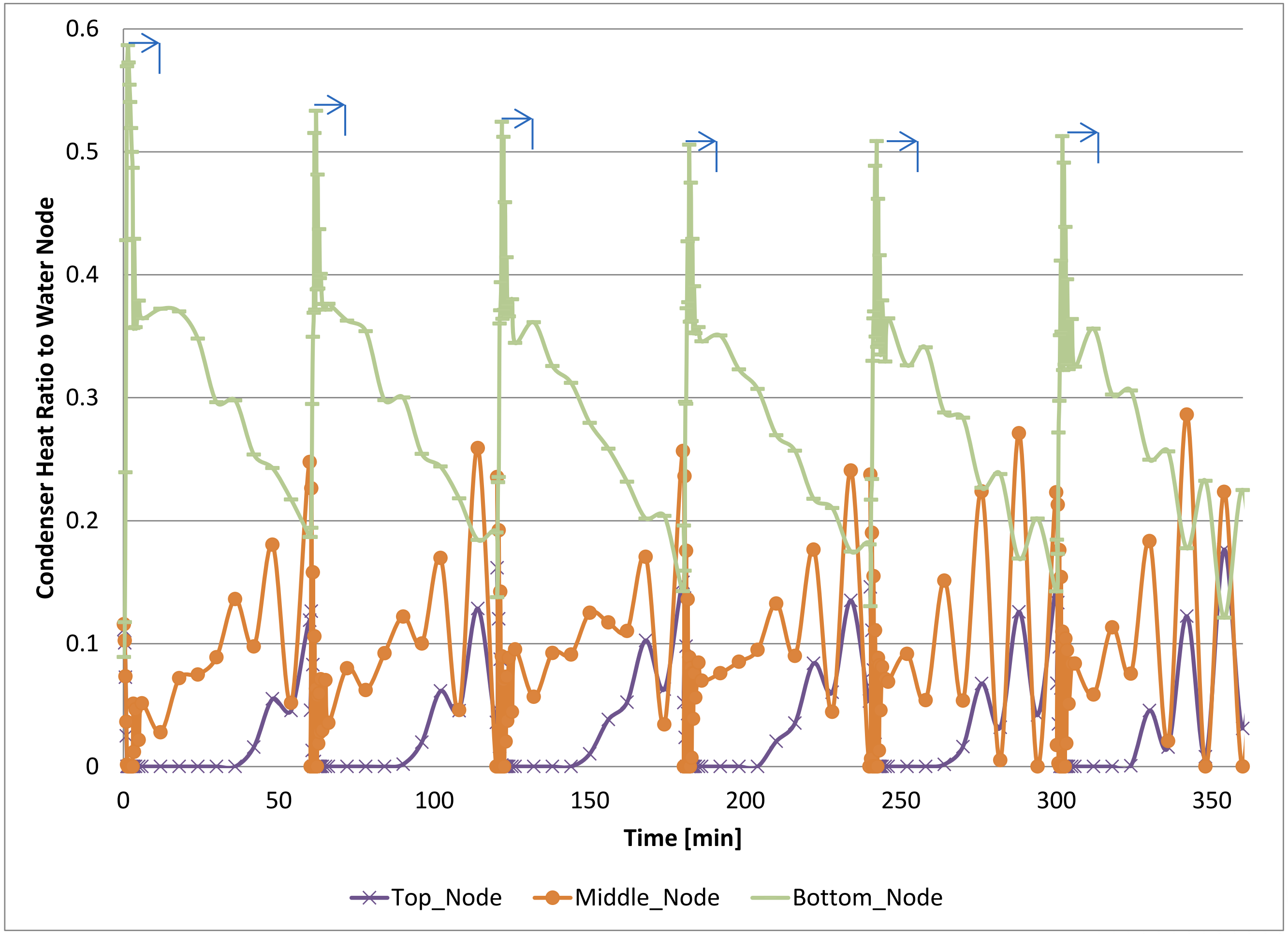
Fraction2

…

Fractionn

*Fraction means percentage of condenser heat to each node

3. Condenser heat fractions to nodes change with time and water draw

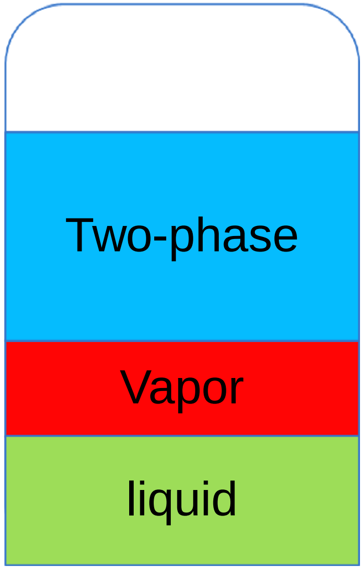


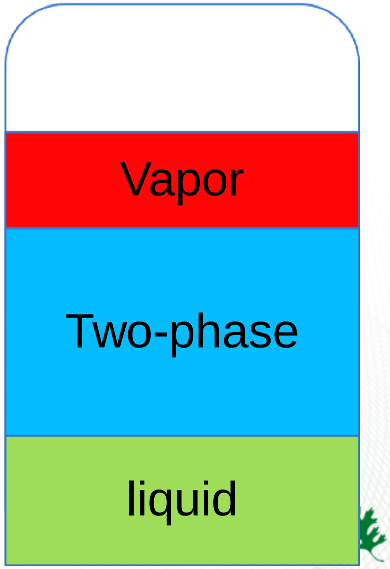
Six water draws
(6-minutes, 3 GPM)

At the beginning of water draw, condenser heat fractions to individual nodes differ the most; at the end of heat pump heat up, the nodal condenser heat fractions are closer together.

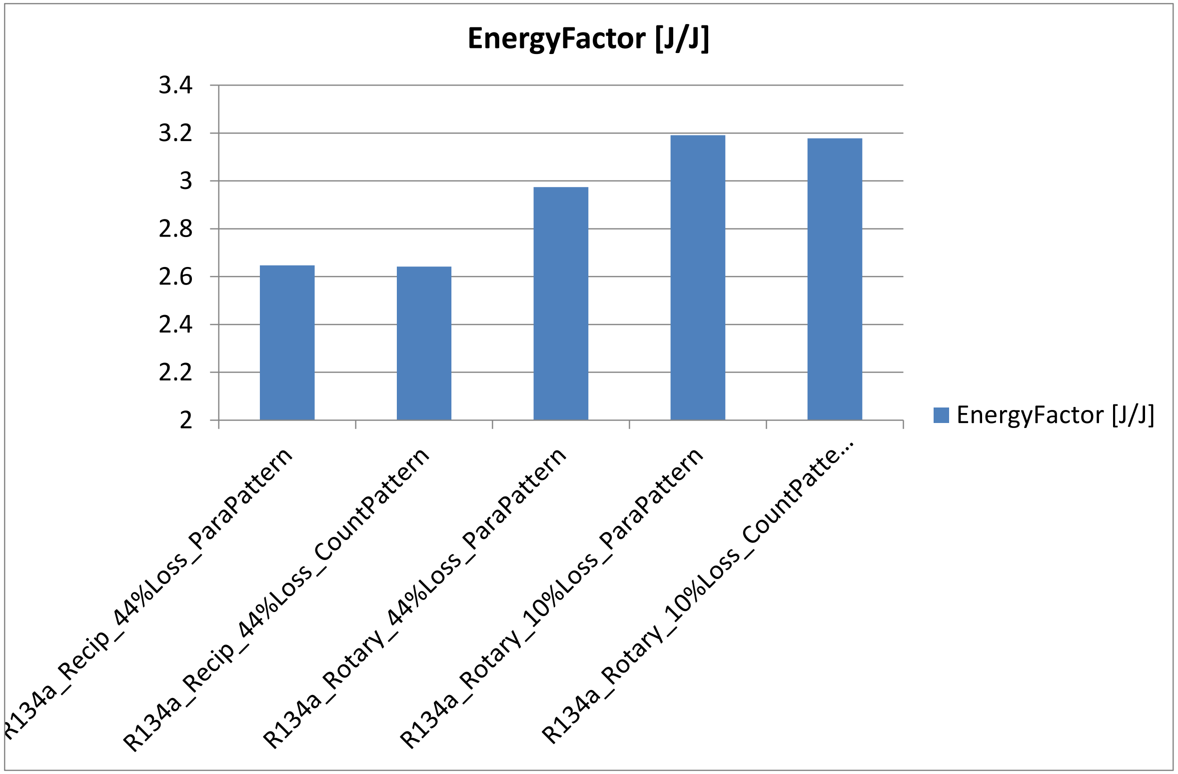
4. Design Case Study

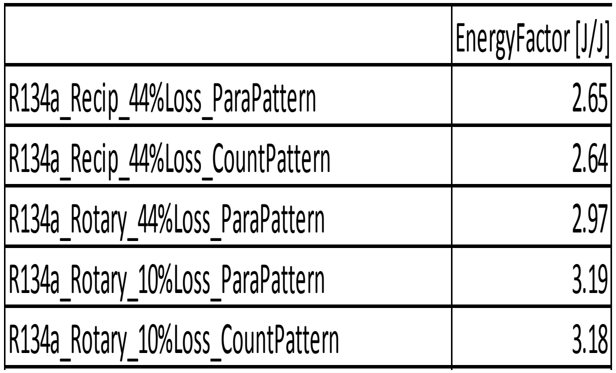
- 90% efficiency, 46-gallon water tank
- Heat pump T-stat at the top: on at 130°F, off at 135°F.
- Electric element at the top: on at 110°F, off at 130°F.
- Two compressors: R-134a, one reciprocating (low efficiency), one rotary compressor (high efficiency), used compressor maps.
- Two compressor heat loss factors (insulation levels): 44%, 10% (thermal insulation on the shell), relative to compressor power
- Two condenser coil wrap patterns:


Parallel vapor to two-phase wrap


Counter vapor to two-phase wrap

4. Predicted 24-hr Energy Factor



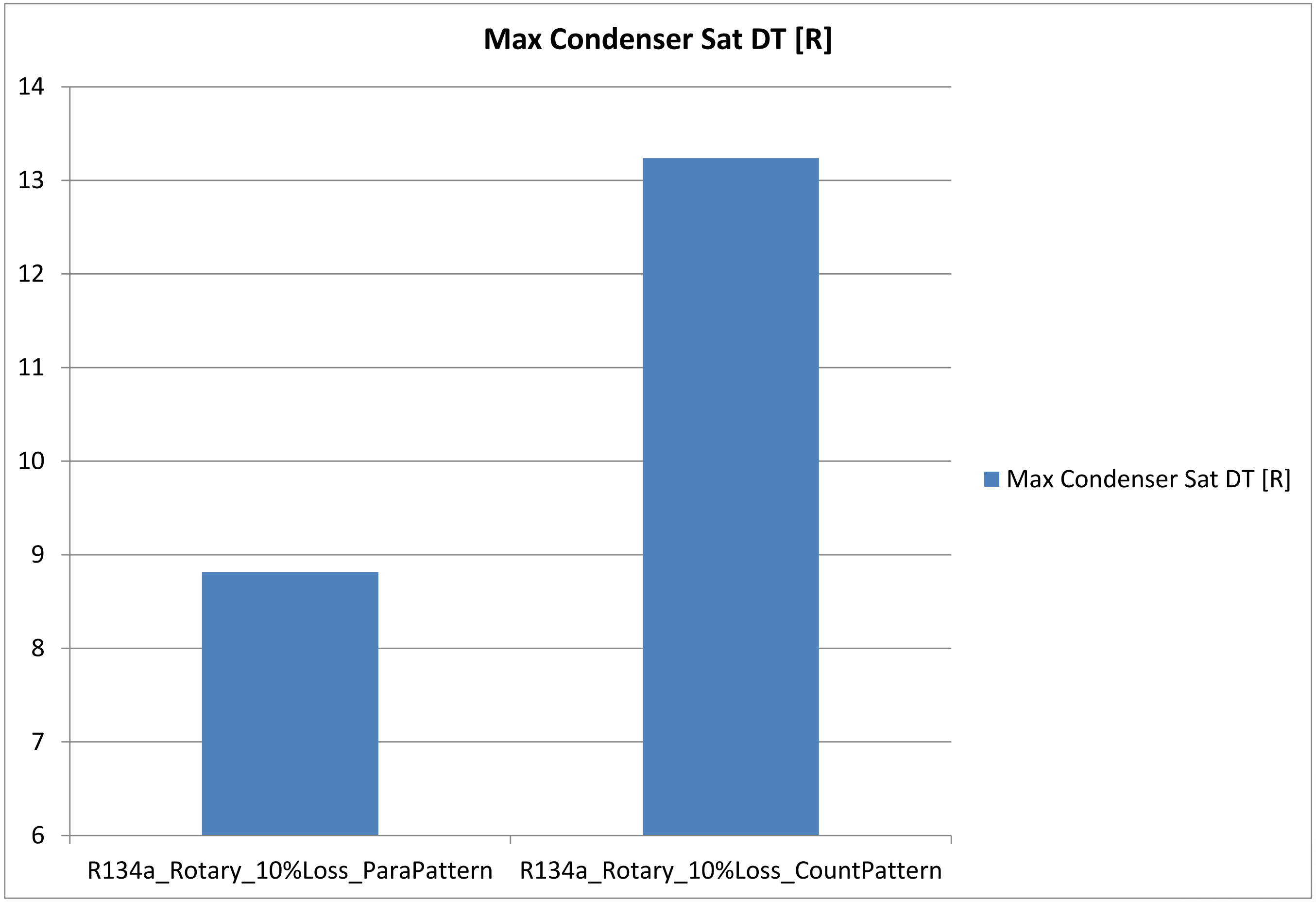


	EnergyFactor [J/J]
R134a_Recip_44%Loss_ParaPattern	2.65
R134a_Recip_44%Loss_CountPattern	2.64
R134a_Rotary_44%Loss_ParaPattern	2.97
R134a_Rotary_10%Loss_ParaPattern	3.19
R134a_Rotary_10%Loss_CountPattern	3.18

-step-by-step design improvement

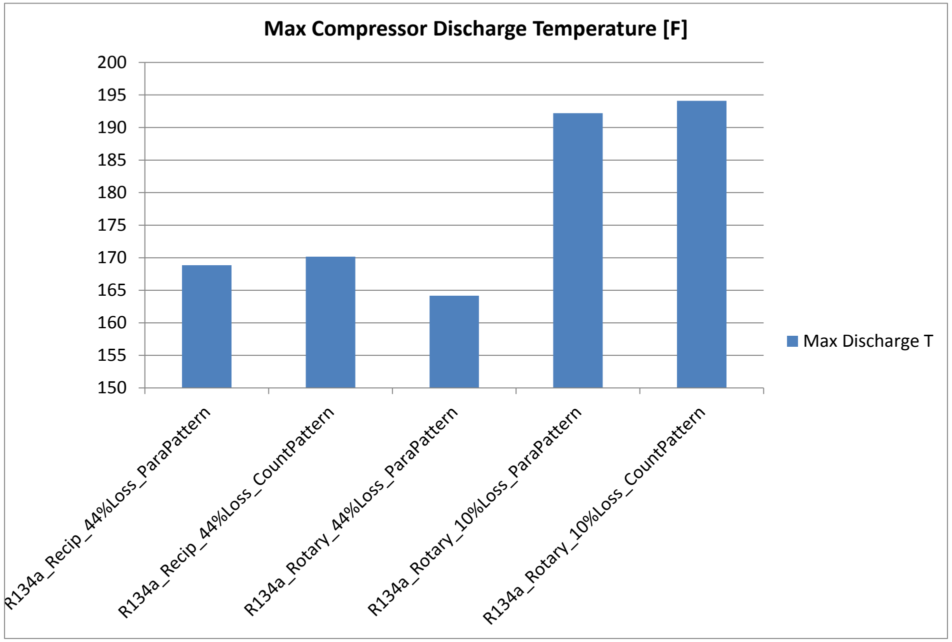
Assists engineers to select components, design heat exchangers before going to the lab.

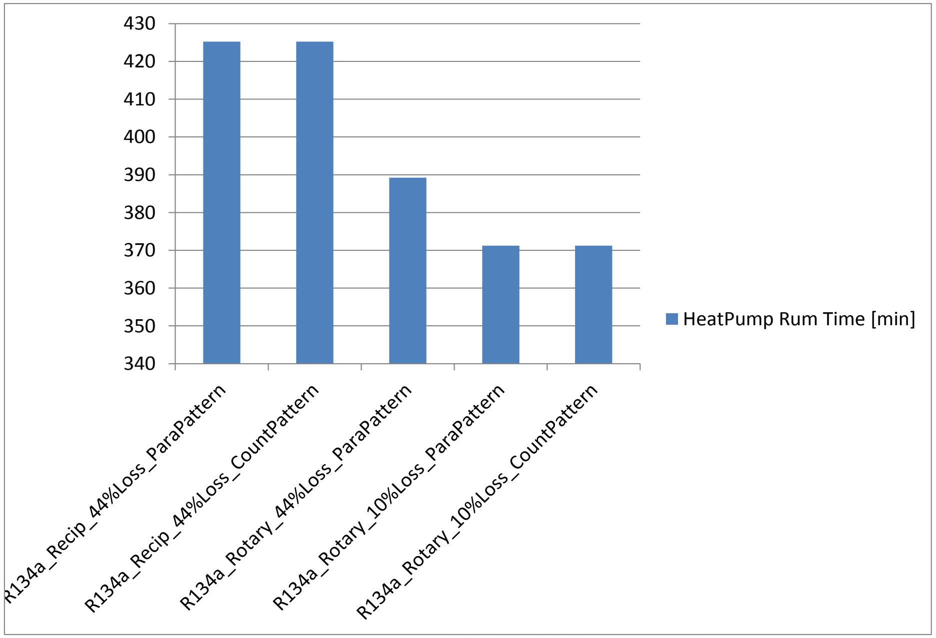
4. Impact of Coil Wrap Pattern



- Counter coil pattern results in longer vapor section and condenser pressure drop, which offsets the benefit of counter-flow heat transfer.

4. Assess Overheat Risk and Compressor Sizing Effects





-Assess compressor overheat risk by predicting Max discharge temperature

-Reveal impact of compressor sizing, heat loss, etc. on total HP run time.

-Smaller compressor unloads heat exchangers, but increases the risk of more supplemental heater use.

5. Summary

- Adding a bulk mixing mechanism to the E+ tank model enables calibration to match measured water stratification after draw events.
- Quasi-steady-state segment-to-segment wrapped tank coil model represents the variable condenser heat distribution to nodes in heating process.
- HPDM is a design tool that can assist product engineers to make decisions before going to the lab.