OAK RIDGE National Laboratory

# Maximum Efficiency Heat Pump Water Heater Based on Low-GWP Hydrofluoroolefin Refrigerants

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U.S. DEPARTMENT OF ENERGY

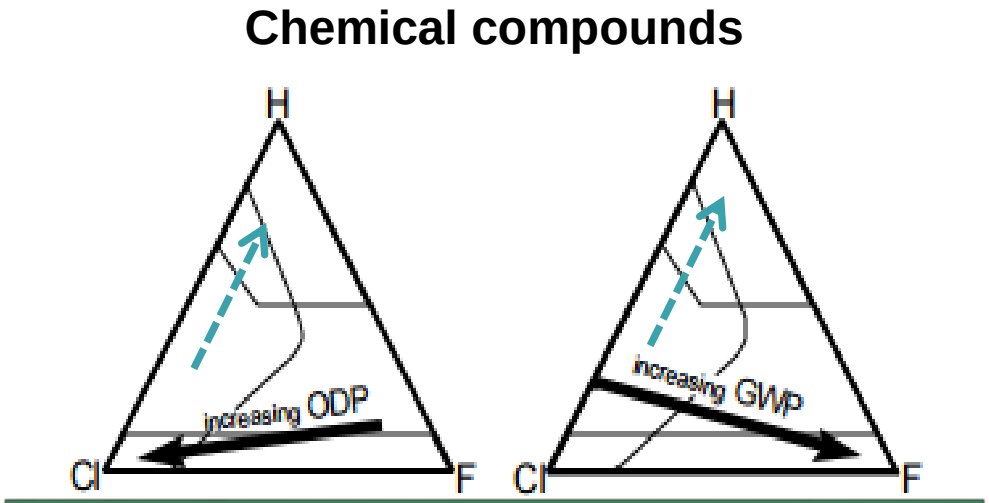
# Content

- Background
- Potential alternative refrigerants
- Model development and results
- Experimental validation
- Conclusions

# Next Generation Refrigerants

| Refrigerant | $GWP_{100}$ |
|---|---|
| $CO_2$ | 1 |
| R-22 | 1760 |
| R-134a | 1300 |
| R-410A | 1924 |

- Hydrofluoroolefins (HFOs)
  - Fluorinated propene isomers
    - R-1234yf ($CF_3CF = CH_2$)
    - R-1234ze ($CF_3CH = CHF$)
  - GWP < 4
  - Mildly flammable




*Away from Chlorine (ODP) and Fluorine (GWP) inevitably leads to flammability*

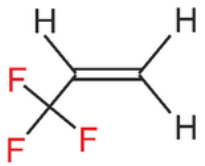
# Goals

Identify appropriate substitute for R-134a as HFCs will phase out:

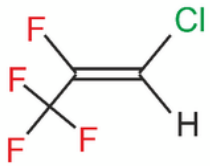
- **Evaluate the potential of HFOs to replace the conventional working fluid (R134a) for a residential hybrid heat pump water heater.**
  - Low GWP, no direct environmental impact
  - No major modification of existing system is desired.
  - Performance FHR and UEF should be comparable.

# Alternative Refrigerants

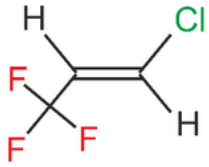
| Refrigerant | Composition (mass %) | at 45 F | | | | | | at 155 F |
|---|---|---|---|---|---|---|---|---|
| | | $T_c$ (K) | $P_c$ (Mpa) | $P_{sat}$ (Mpa) | $h_{fg}$ (KJ/kg) | $P_{vap}$ (kg/m$^3$) | Vol. Cap (KJ/m$^3$) | $P_{sat}$ (Mpa) |
| **R134a** | Pure | 374.21 | 4.06 | 0.3774 | 193.17 | 18.66 | **3604.55** | 2.04 |
| **R1234yf** | Pure | 367.85 | 3.38 | 0.4006 | 158.52 | 22.253 | **3527.55** | 1.9725 |
| **R1234ze** | Pure | 382.51 | 3.64 | 0.2803 | 179.49 | 15.004 | **2693.07** | 1.551 |



HFO-1243zf

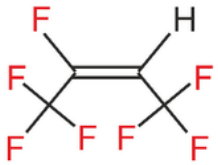


HCFO-1224yd

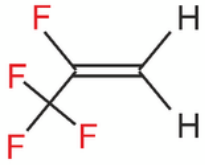


HCFO-1233zd

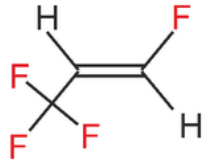
HFO-1216



HFO-1336mzz(Z)



HFO-1234yf



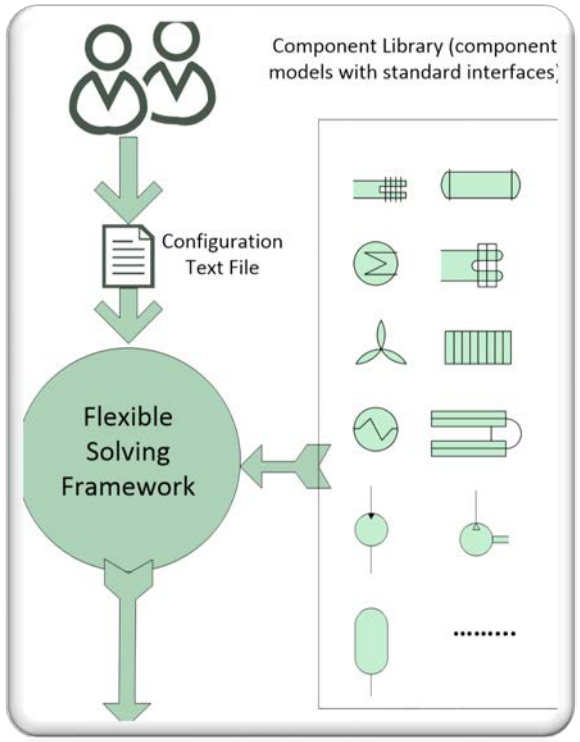
HFO-1234ze(E)

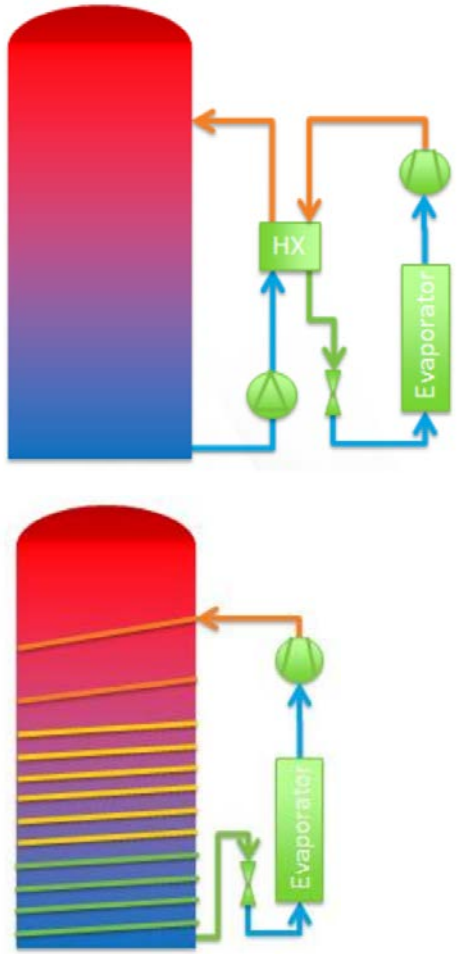
HFO-1234ze(Z)

# Model development- ORNL HPDM

**Component-Based**

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



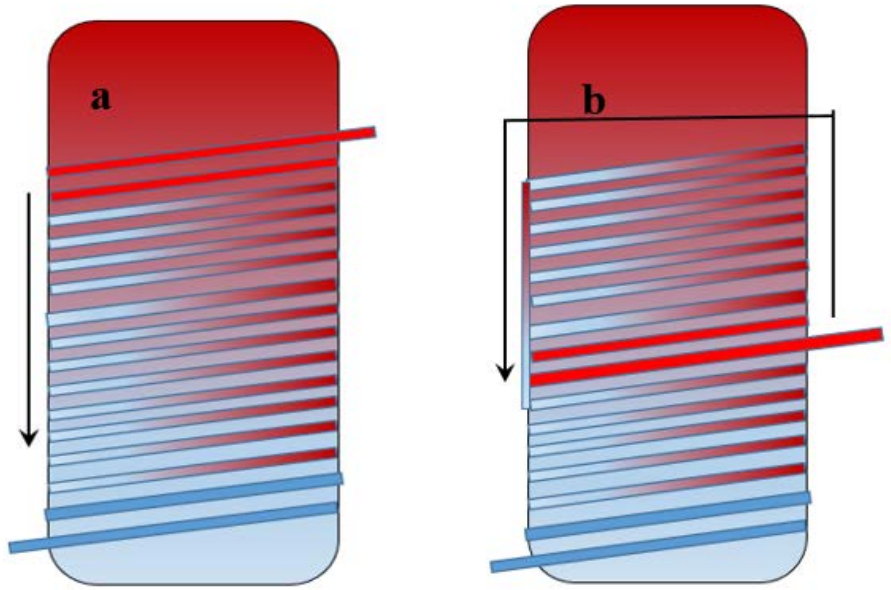




*Automatically connect components into required system configuration by user input file.*

B. Shen, K. Nawaz, A. Elatar, V. Baxter, "Development and Validation of Quasi-Steady-State Heat Pump Water Heater Model Having Stratified Water Tank and Wrapped-Tank Condenser" International Journal of Refrigeration, 2018, 87,78-90.

# Design Parameters

- 46-gallon water tank
- Heat pump T-stat at the top: on at 115 °F, off at 125 °F.
- Electric element at the top: on at 110°F, off at 125 °F.
- Two different evaporator sizes and evaporator flow rate
- Two different heat loss factors from tank
- Two different condenser coil wrap patterns
- Two different condenser tube sizes

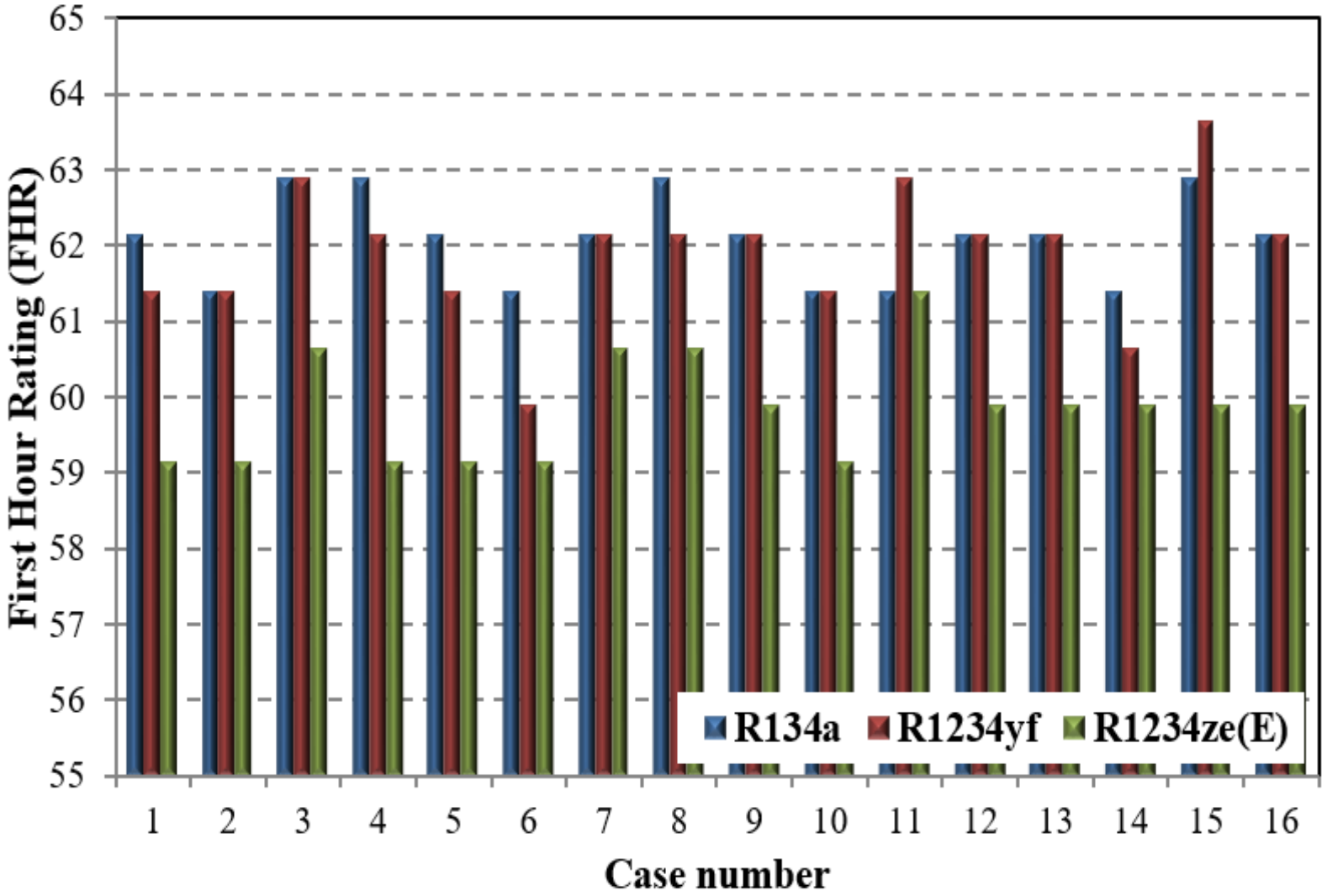



Condenser wrap configurations (a) counter flow (b) parallel-counter flow

# Design Parameters

| Case number | Wrap pattern | Evaporator size* | Tank insulation effectiveness (%) | Condenser tube size (inches) |
|---|---|---|---|---|
| 1 | Parallel-counter | 1 Evap | 90 | 0.31 |
| 2 | Parallel-counter | 1 Evap | 90 | 0.50 |
| 3 | Parallel-counter | 2 Evap | 90 | 0.31 |
| 4 | Parallel-counter | 2 Evap | 90 | 0.50 |
| 5 | Parallel-counter | 1 Evap | 95 | 0.31 |
| 6 | Parallel-counter | 1 Evap | 95 | 0.50 |
| 7 | Parallel-counter | 2 Evap | 95 | 0.31 |
| 8 | Parallel-counter | 2 Evap | 95 | 0.50 |
| 9 | Counter | 1 Evap | 90 | 0.31 |
| 10 | Counter | 1 Evap | 90 | 0.50 |
| 11 | Counter | 2 Evap | 90 | 0.31 |
| 12 | Counter | 2 Evap | 90 | 0.50 |
| 13 | Counter | 1 Evap | 95 | 0.31 |
| 14 | Counter | 1 Evap | 95 | 0.50 |
| 15 | Counter | 2 Evap | 95 | 0.31 |
| 16 | Counter | 2 Evap | 95 | 0.50 |

# First Hour Rating (FHR)



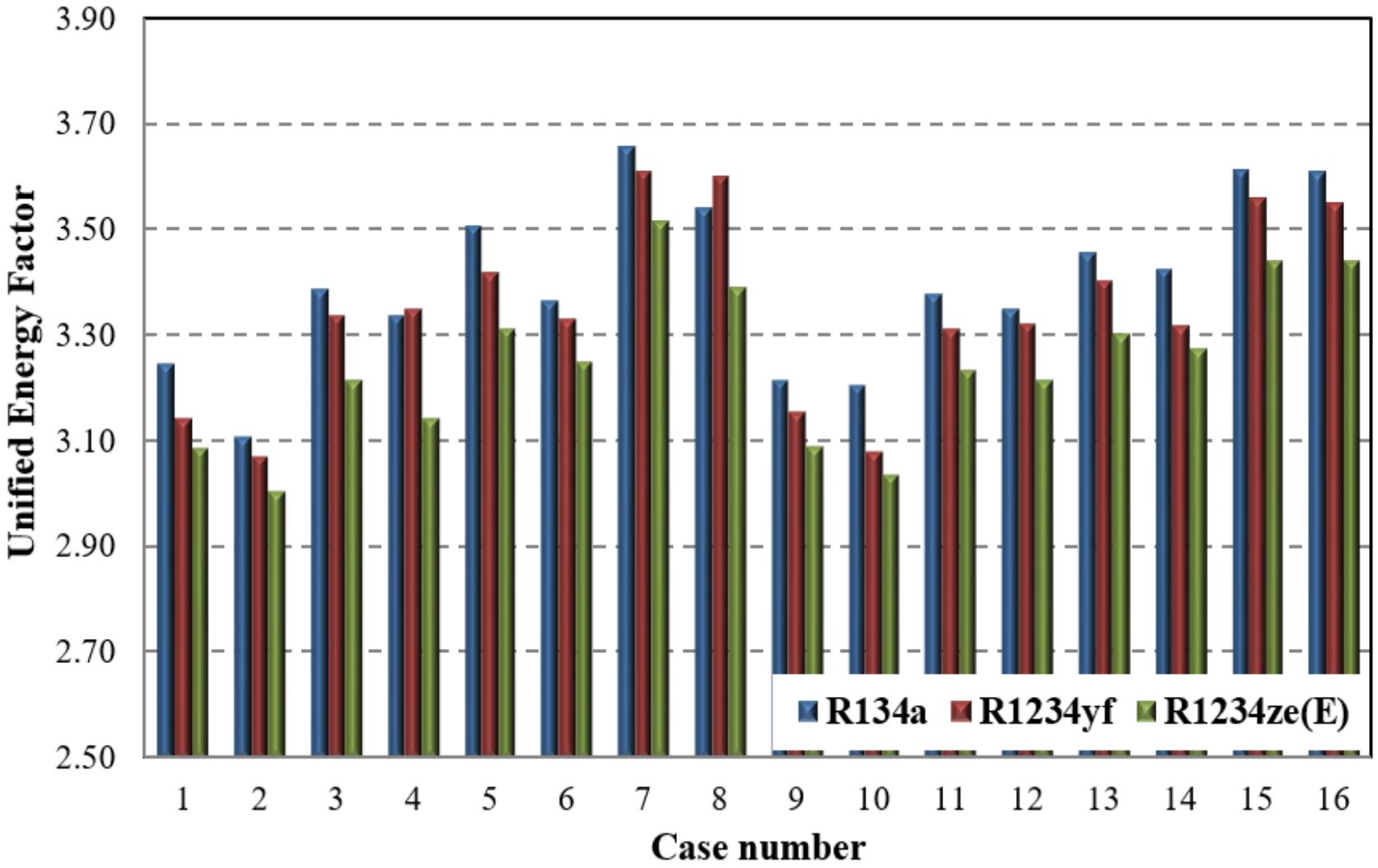
# Performance Evaluation Criteria

| FHR greater or equal to (gals) | FHR less than (gals) | Draw pattern for 24-hr UEF |
|---|---|---|
| **0** | 20 | Point of use |
| **20** | 55 | Low usage |
| **55** | 80 | Medium usage |
| **80** | Max | High usage |

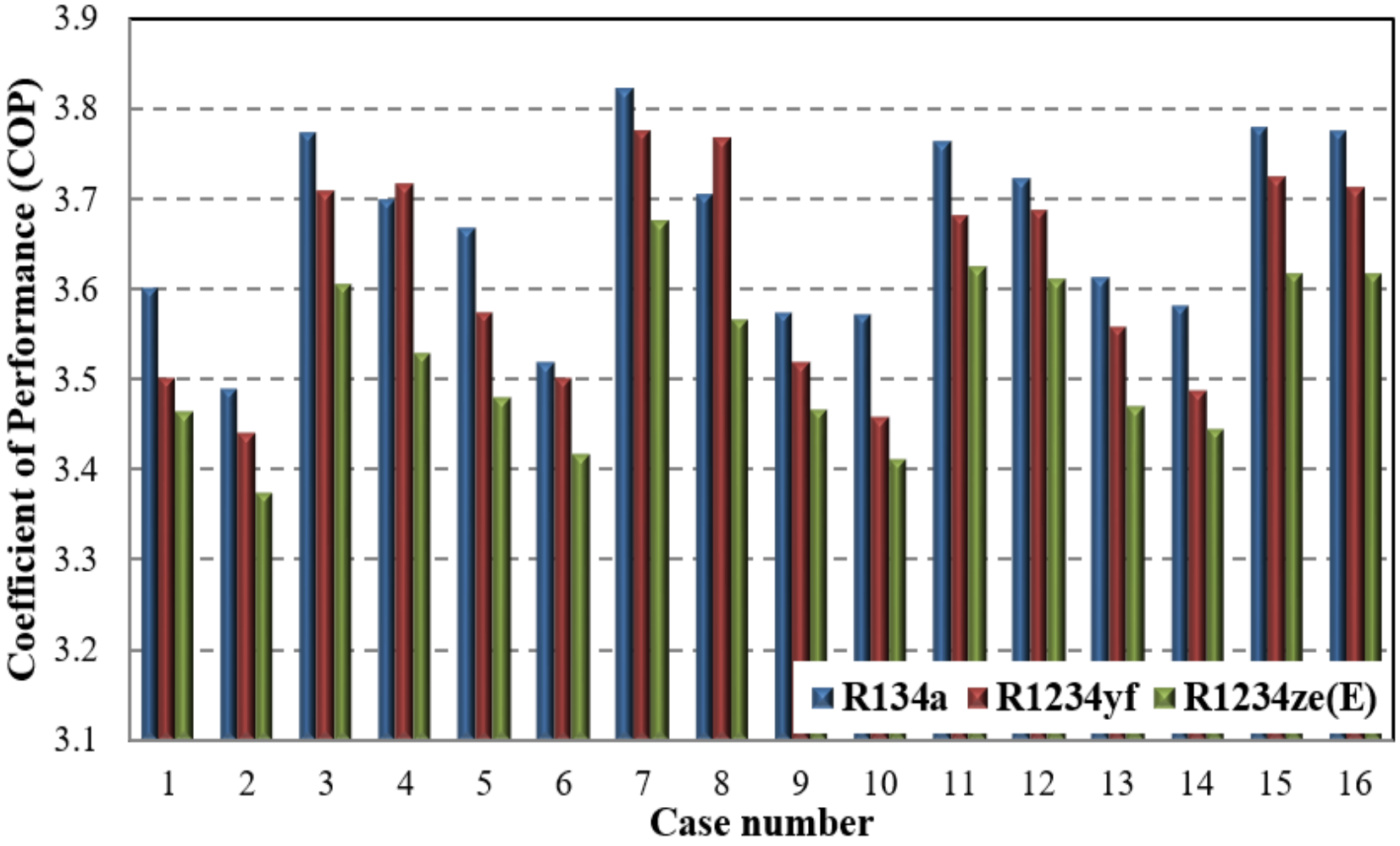
| Draw Number | Time During Test (hh:mm) | Volume (gals/L) | Flow Rate (GPM/LPM) |
|---|---|---|---|
| **1** | 00:00 | 15.0 (56.8) | 1.7 (6.5) |
| **2** | 00:30 | 2.0 (7.6) | 1 (3.8) |
| **3** | 01:40 | 9.0 (34.1) | 1.7 (6.5) |
| **4** | 10:30 | 9.0 (34.1) | 1.7 (6.5) |
| **5** | 11:30 | 5.0 (18.9) | 1.7 (6.5) |
| **6** | 12:00 | 1.0 (3.8) | 1 (3.8) |
| **7** | 12:45 | 1.0 (3.8) | 1 (3.8) |
| **8** | 12:50 | 1.0 (3.8) | 1 (3.8) |
| **9** | 16:00 | 1.0 (3.8) | 1 (3.8) |
| **10** | 16:15 | 2.0 (7.6) | 1 (3.8) |
| **11** | 16:45 | 2.0 (7.6) | 1.7 (6.5) |
| **12** | 17:00 | 7.0 (26.5) | 1.7 (6.5) |
| **Total Volume Drawn Per Day: 55 gallons (208 L)** | | | |

**Medium usage draw pattern**

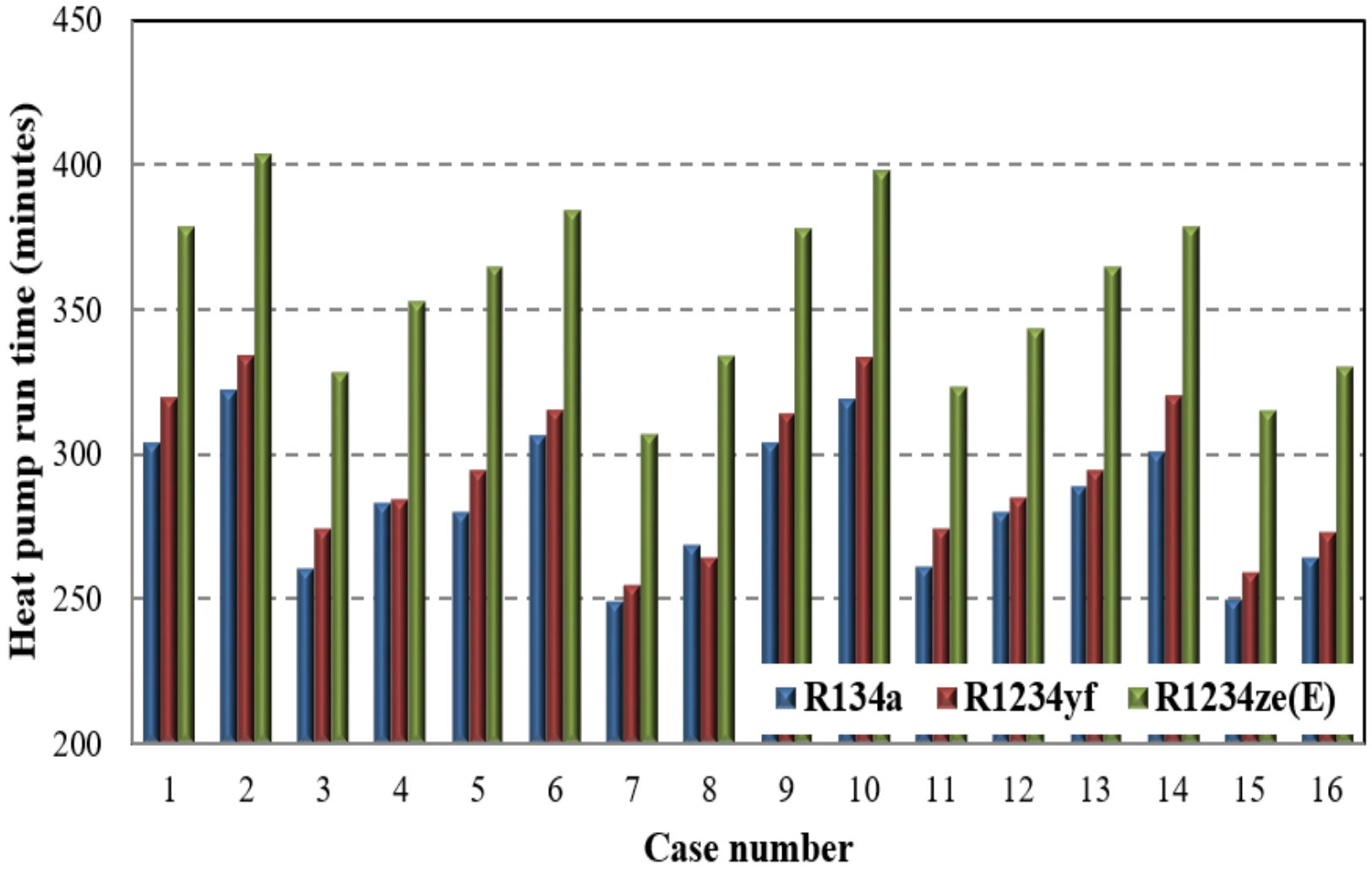
# Unified Energy Factor



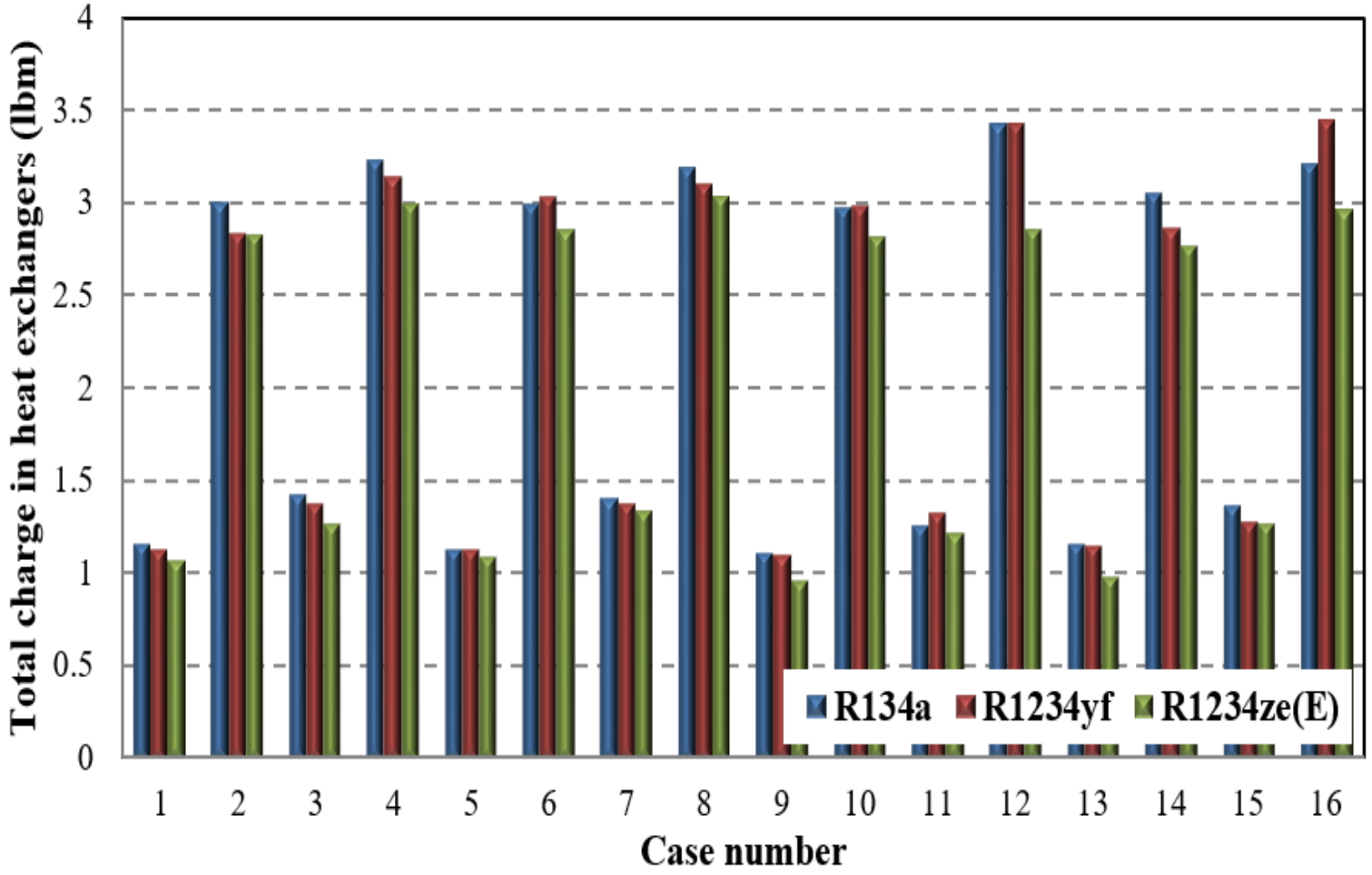
# Coefficient of Performance



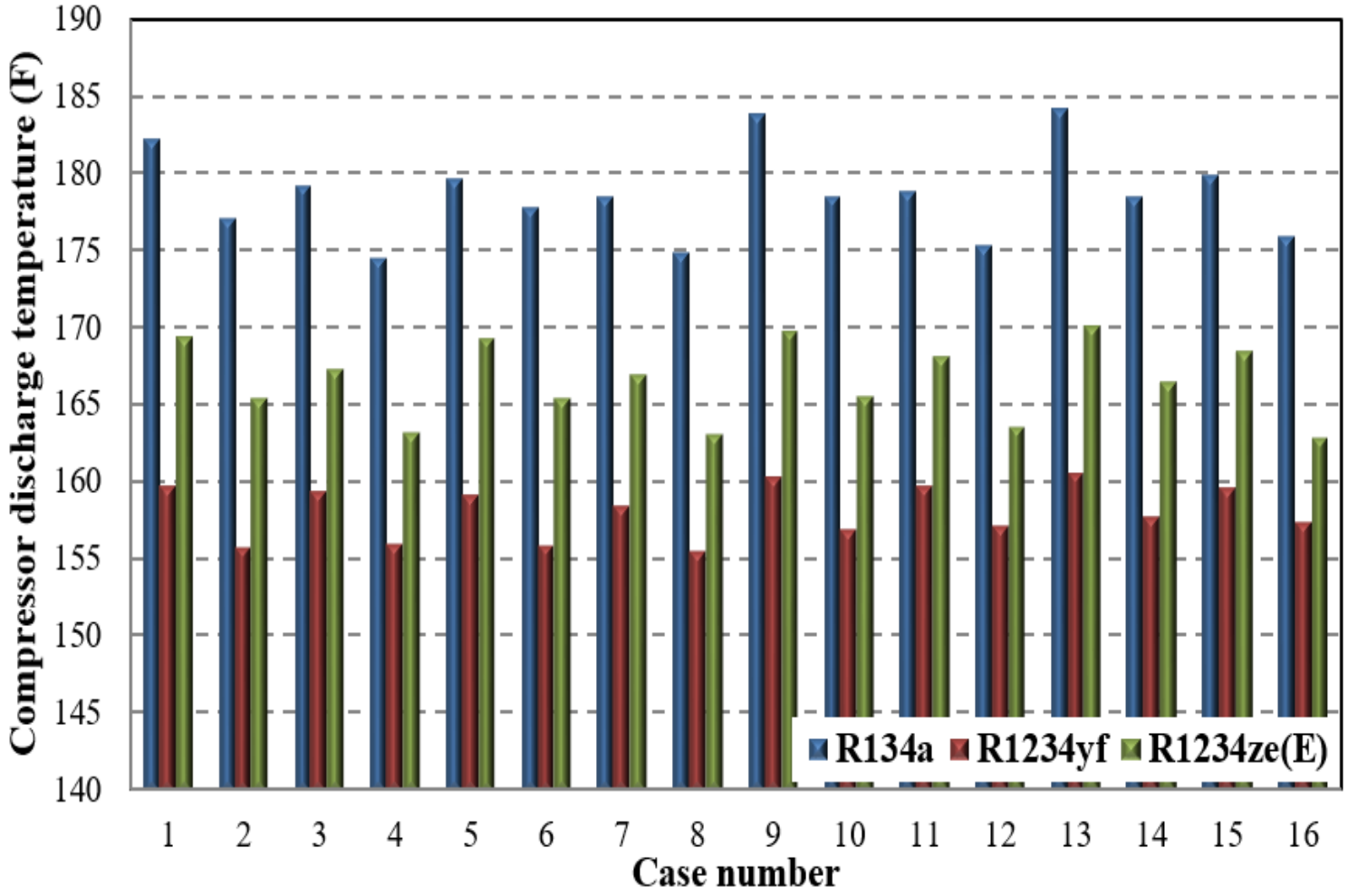
# Heat Pump Run Time



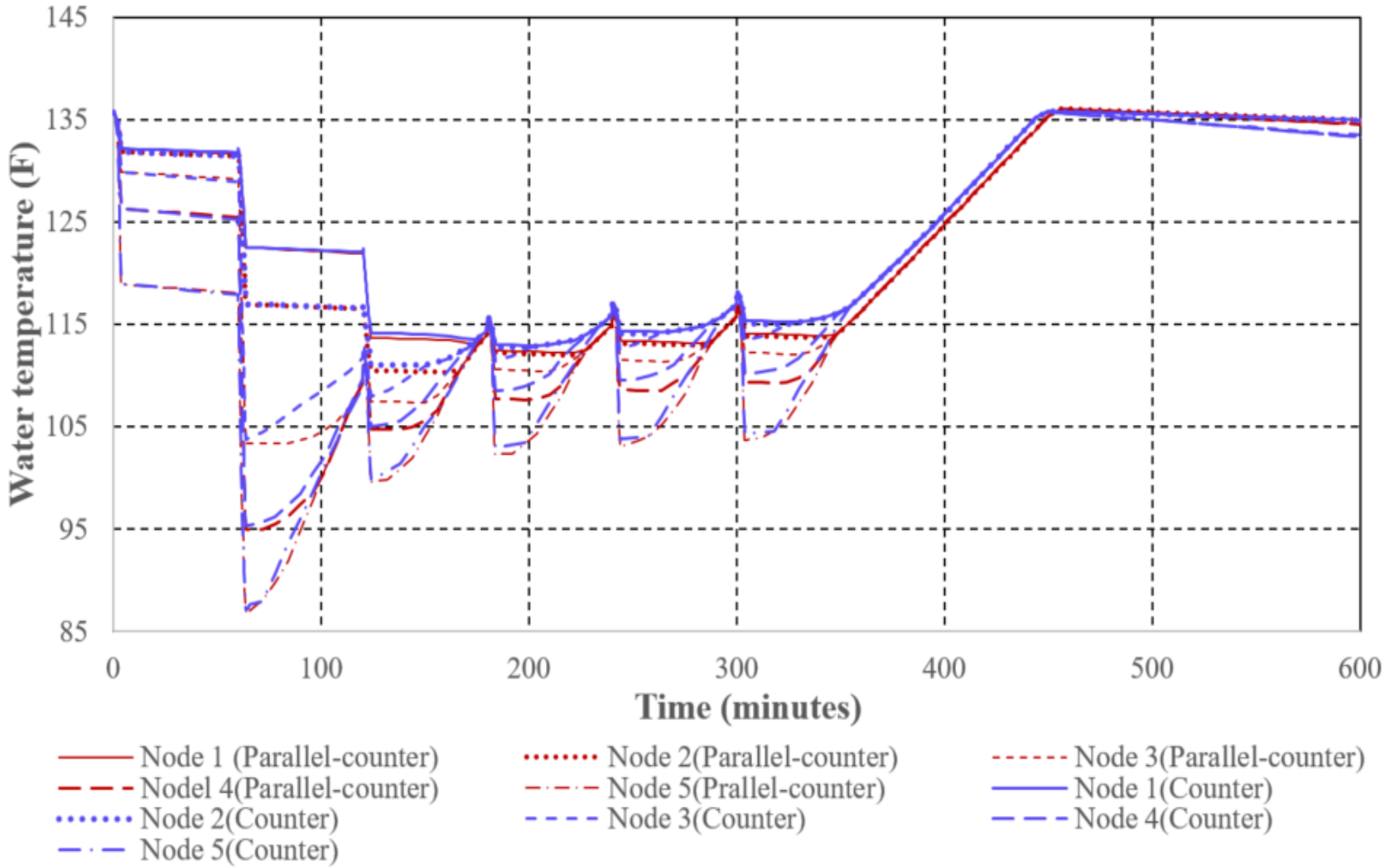
# Total Charge in the Condenser and Evaporator



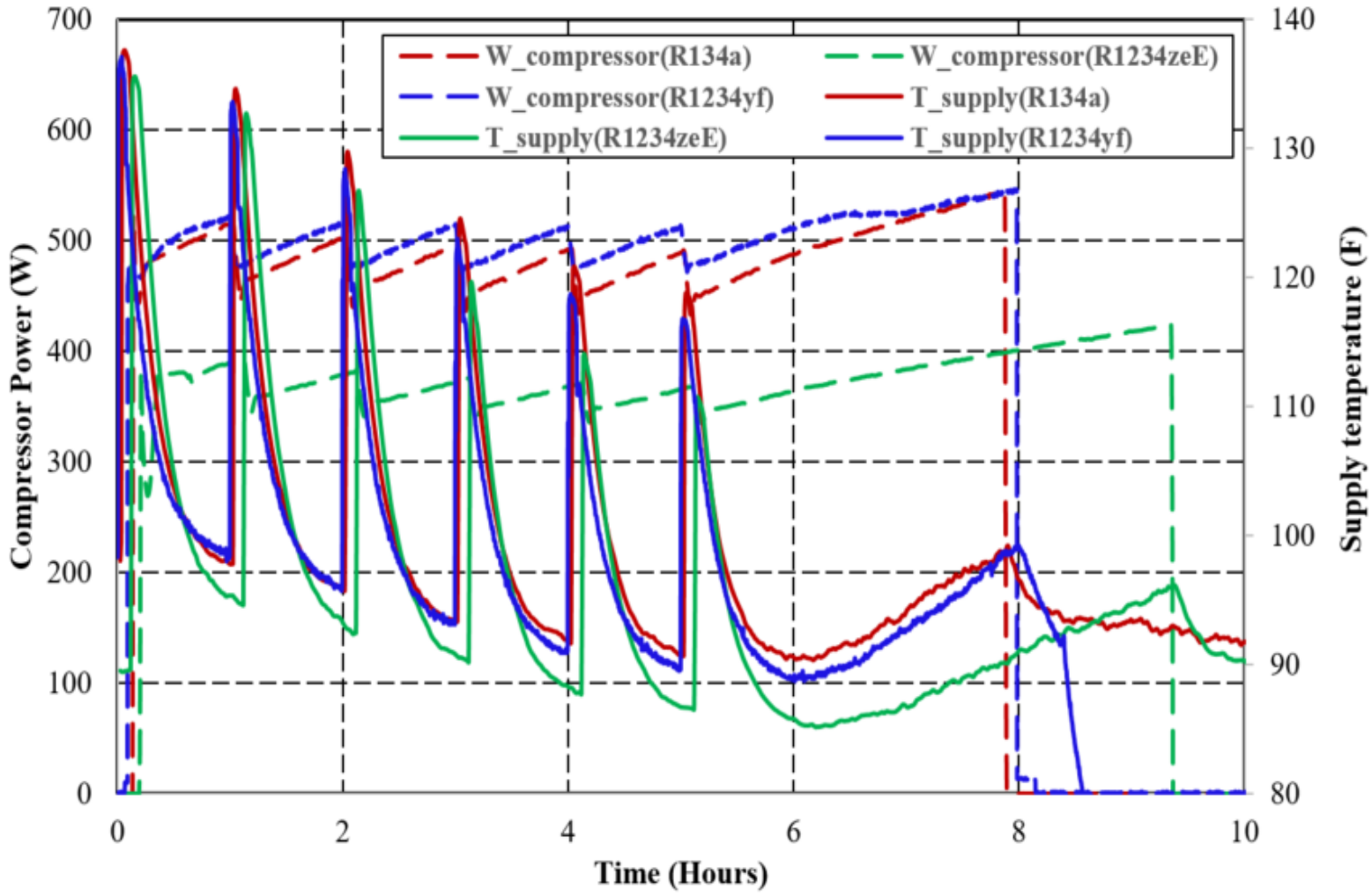
# Max Compressor Discharge Temperature



# Condenser wrap configuration- Impact on stratification

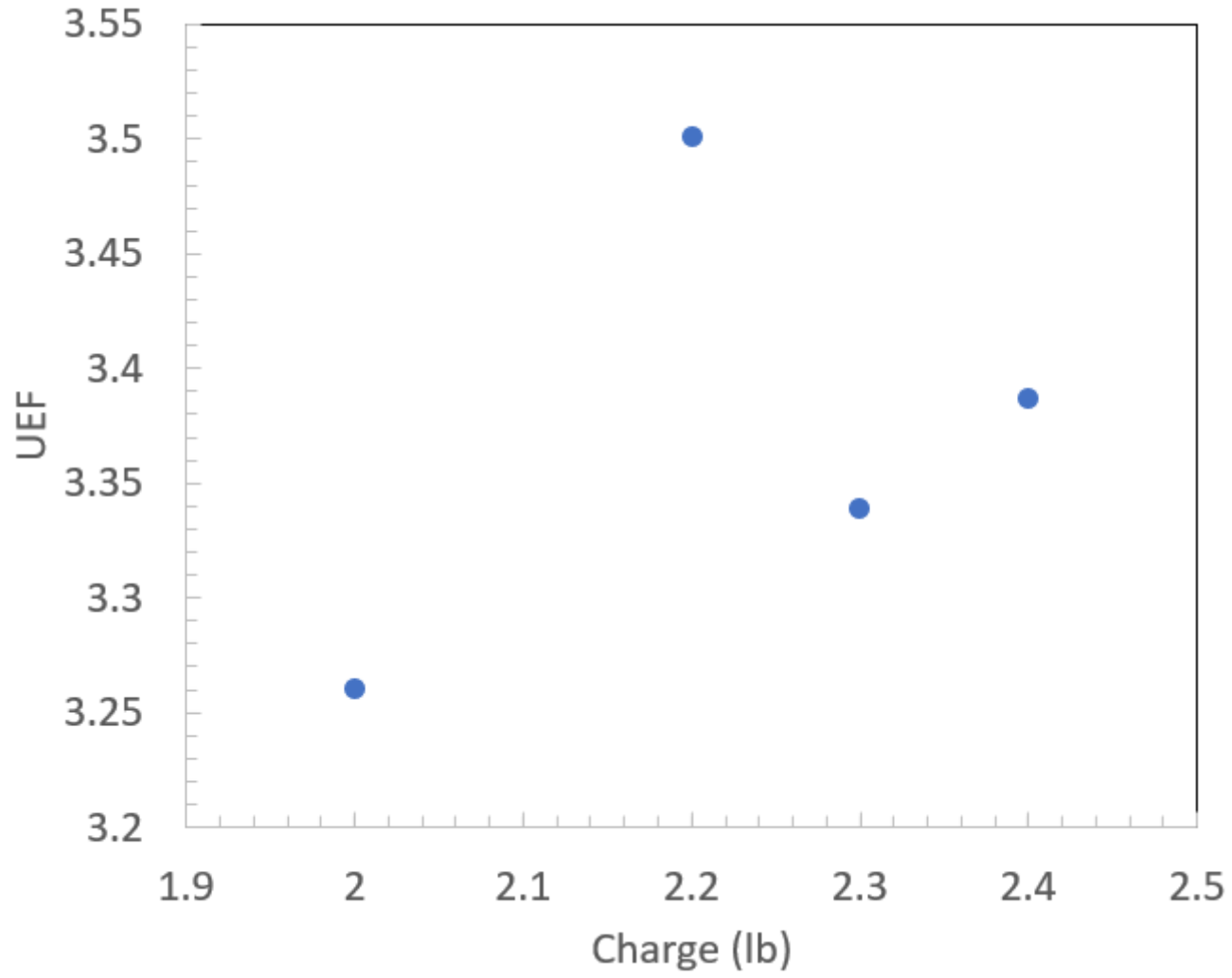


# Experimental Validation

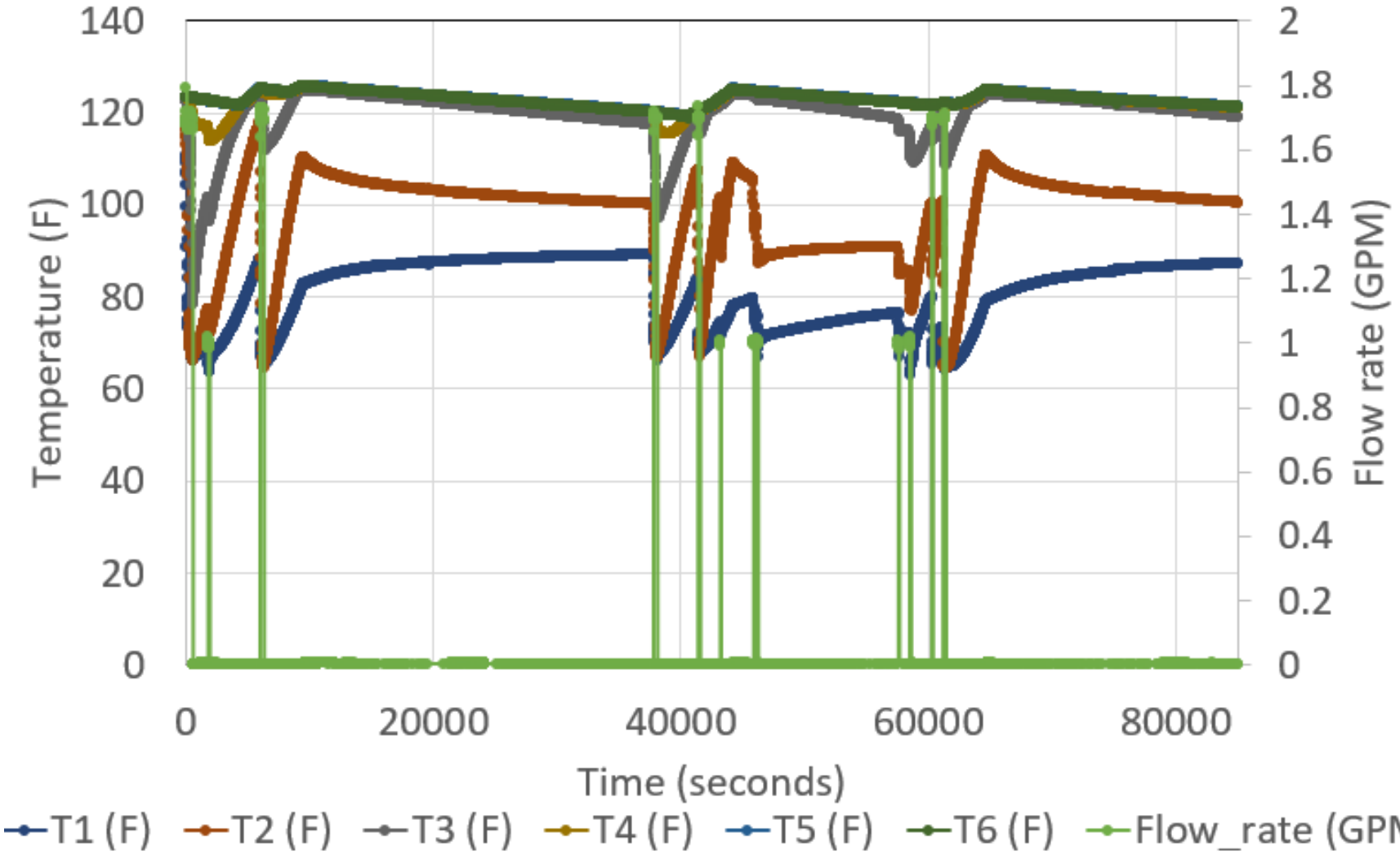


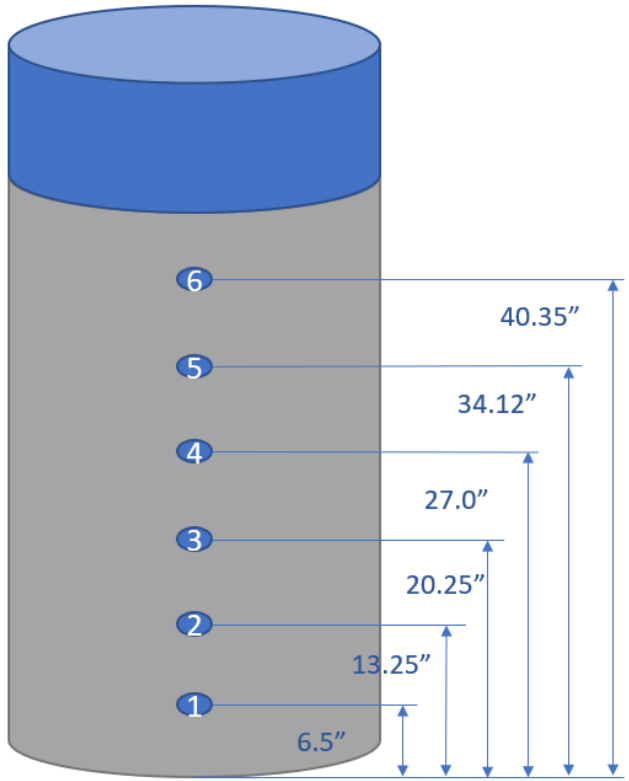

**Old study: Baxter et al., 2016**

# Experimental Validation- Charge Optimization



# Experimental Validation



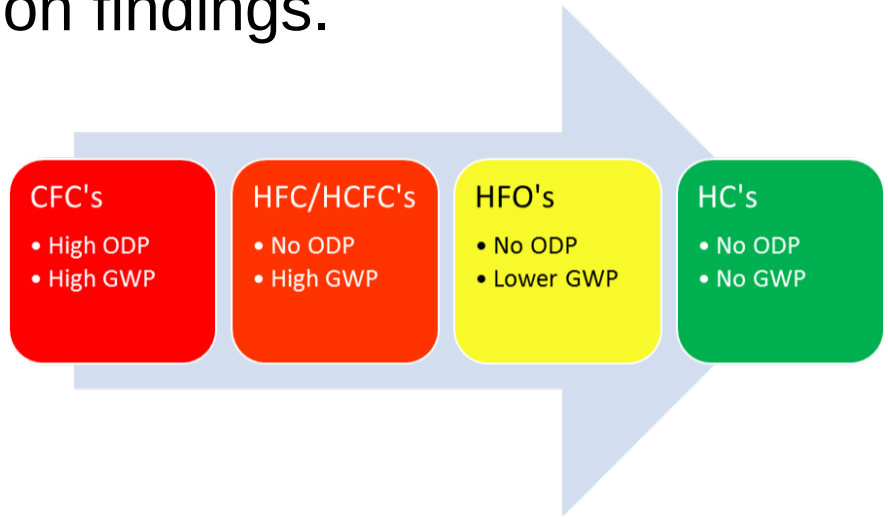
# Experimental Validation

| Parameter | R134a | R1234yf |
|---|---|---|
| Optimum refrigerant charge | 2.3 | 2.2 |
| First Hour Rating (FHR) | 66 | 68 |
| Unified Energy Factor | 3.44 | 3.40 |

*including 0.70 lbs of charge in flow meter line

# Conclusions

- R1234yf is a feasible working fluid for residential HPWHs with comparable performance as R134a.
- R1234ze (E) has reduced capacity- System modification is required for comparable capacity.
- The experimental results validate the simulation findings.



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# THANK YOU

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