JAIN RESEARCH LAB

Robust Modeling of A Multi-Functional Cold Climate Heat Pump System

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OVERVIEW

Thermal energy storage (TES) can help reduce energy costs and greenhouse gas emissions. However, **existing approaches for the residential building sector do not take full advantage of what TES has to offer regarding peak reduction, load shifting, and electrification of space and water heating.** Major barriers to efficient operation of a residential heat pump system include system defrost and general cold climate operation. Both increase energy consumption and may require backup heating.

To improve viability of TES integration with residential heat pumps, **this work considers design and control of a multi-functional system architecture** that utilizes a valve and pump assembly to reconfigure the system into different operation modes that can enable operation that optimally balances efficiency, operating cost, human comfort, and system cost.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Laughman, C. R., & Qiao, H. (2017). On the influence of state selection on mass conservation in dynamic vapour compression cycle models. *Mathematical and Computer Modelling of Dynamical Systems*, 1–22.

[2] McLinden et al., 2003. The REFPROP Database for the Thermophysical Properties of Refrigerants. *International Control of Refrigeration.*

[3] Bell et al., 2015. A generalized moving-boundary algorithm to predict the heat transfer rate of counterflow heat exchangers for any phase configuration. *Applied Thermal Engineering 79, 192-201.*

System Diagram

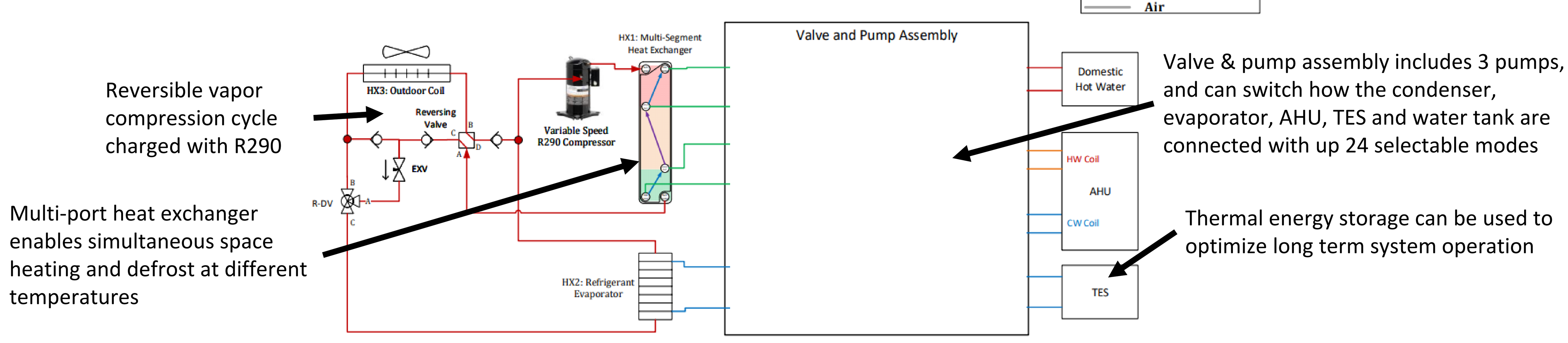

Figure 1: *Multi-Functional HVAC system. Image courtesy of Dr. Juan Catano, National Renewable Energy Laboratory*

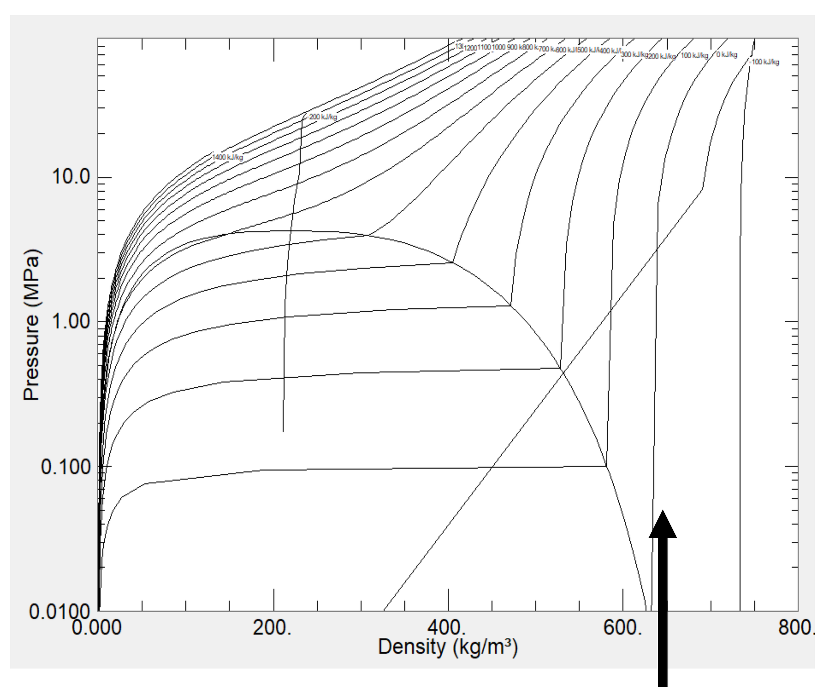

Figure 2: The highest densities are in the compressed liquid and low-quality region. Choosing ρ, P as the coordinate frame allows precise resolution at high densities, which prevents significant error in mass conservation [1]. Image produced using REFPROP [2].

Spotlight Model: Finite Volume Plate HX

A finite volume plate heat exchanger (FV HX) model has been developed with numerical robustness and efficiency in mind. The dynamics are formulated with density (ρ) and pressure (P) as the dynamic states to ensure mass conservation; see Figure 2.

Equation 1: *Governing dynamics of the FV HX formulated in the ρ, P coordinate frame.*

$$\begin{bmatrix} \dot{E}_s \\ \dot{E}_m \\ V_r\dot{\rho} \\ \rho V_r \frac{\partial u_r}{\partial P_r}\dot{P} \end{bmatrix} = \begin{bmatrix} \dot{m}_s c_p (T_s^{in}-T_s) + \dot{Q}_{ms} \\ \dot{Q}_m^k - \dot{Q}_m^{k+1} - \dot{Q}_{ms} - \dot{Q}_{mr} \\ \dot{m}_{in} - \dot{m}_{out} \\ \dot{m}_{in} h_r^{in} - \dot{m}_{out} h_r + \dot{Q}_{mr} - V_r \dot{\rho} \left(u_r + \rho_r \frac{\partial u_r}{\partial \rho_r}\right) \end{bmatrix}$$

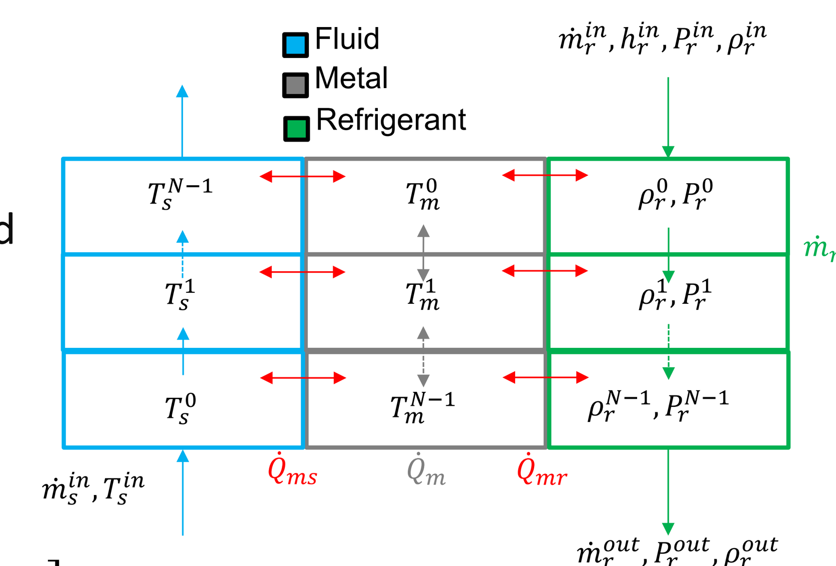

Figure 3: *Schematic of the FV HX in a counter-flow arrangement. In addition to energy balance on each control volume (CV), the mass of each refrigerant CV is tracked.*

Software

With the component models complete, the next step is to construct the system model. The scale of the system requires significant compute for even the most fundamental tasks. As such, a strong focus has been placed on overall program workflow to maximize computation efficiency.

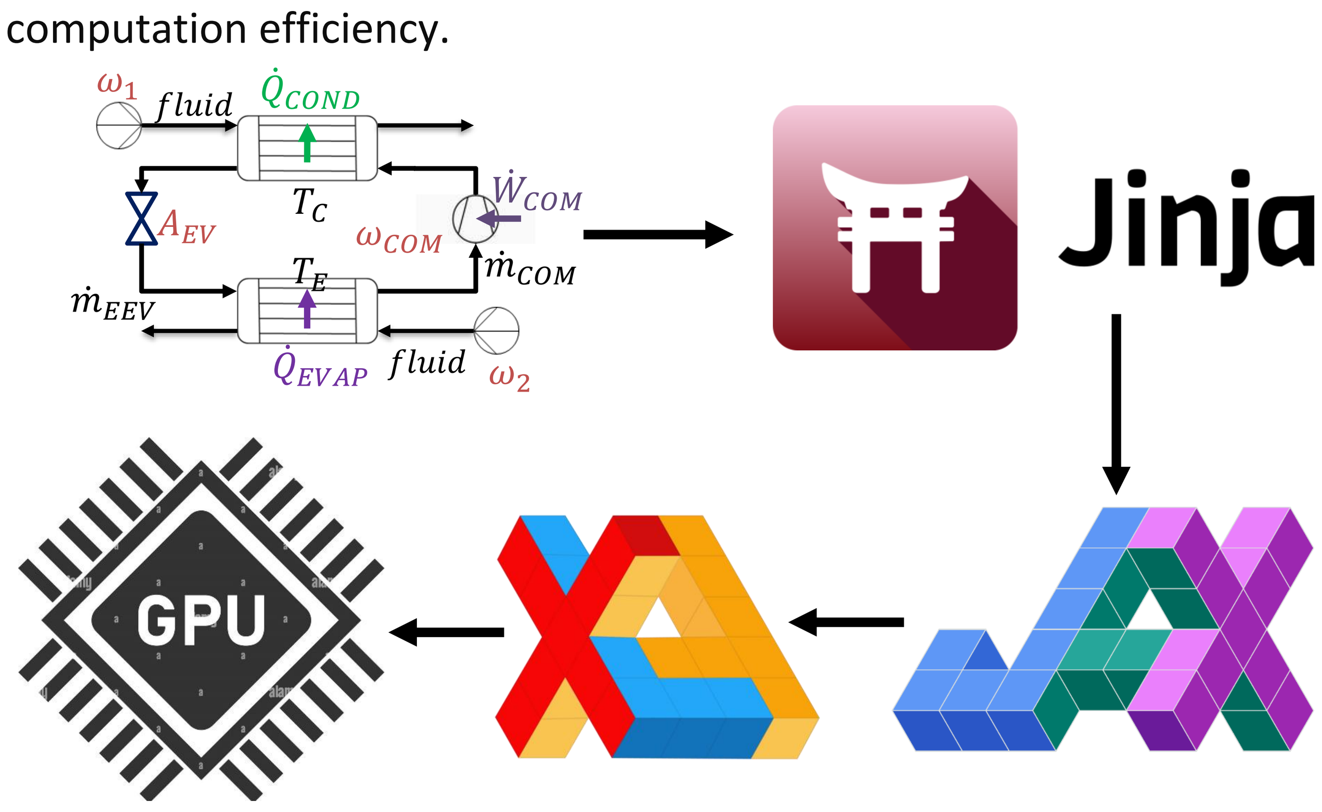

Figure 4: *Model Construction Workflow: (1) Define system with custom system template definition; (2) Use Jinja templating engine to render code; (3) Use JAX machine learning library to apply function transformations and represent functions as computational graphs; (4) Use JAX-XLA (Accelerated linear algebra) to compile code; (5) Parallelize code by running on GPU targets.*

Steady State Solution for FV HX

A robust way to initialize a VCC to a realistic condition is to pick an appropriate steady state condition. This requires solving a system of implicit equations. Figure 5 shows how an approximate solution to this system of equations can be reduced to a sequence of 1d root finding problems.

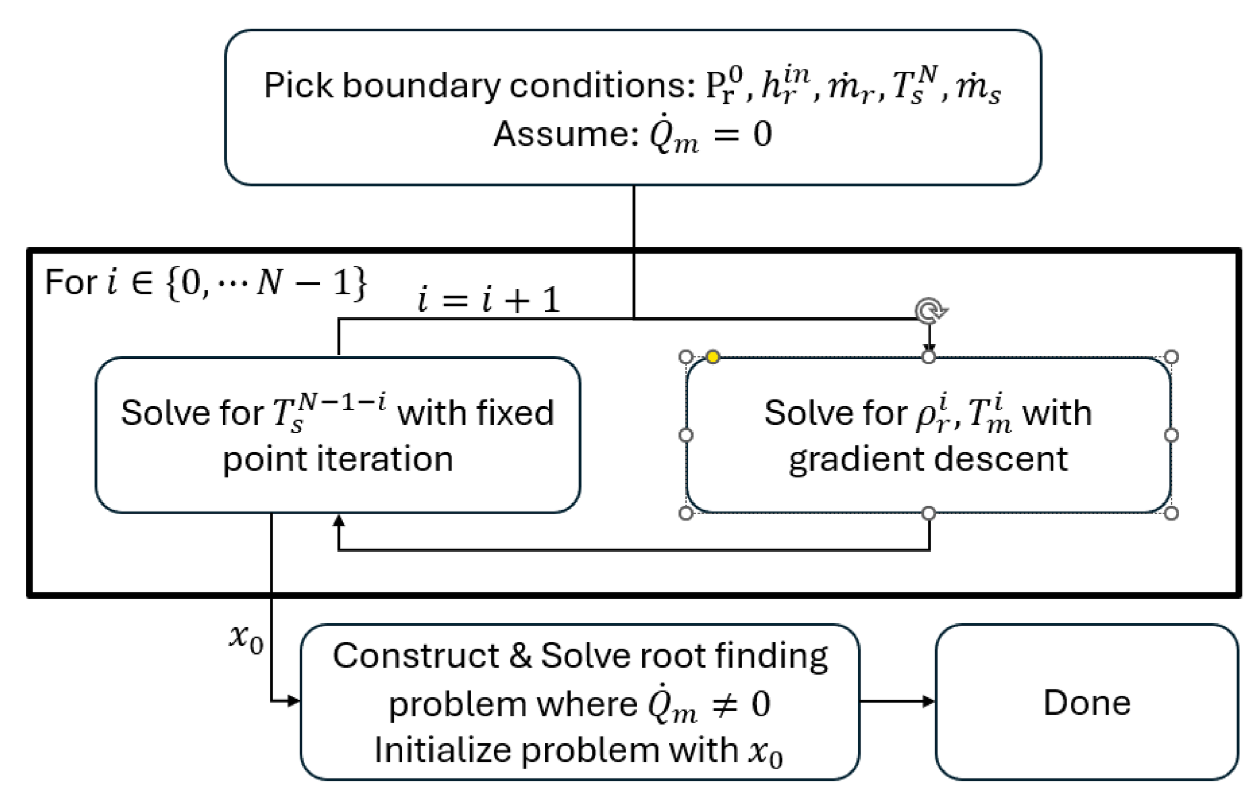

Figure 5: *Algorithm for root finding approach for finite volume heat exchanger.*

Initialization

- The dynamics of a vapor compression cycle are sensitive to the initial conditions.
- A robust solution method has been implemented to obtain steady-state operation of the FV HX in the software paradigm explained above.

Figure 6 is generated by solving 10,000 steady-state problems for the HX with a robust root finding approach. The sweep took 17 seconds on an Intel i7-13700 CPU, without GPU support.

Table 1: *Fixed boundary conditions for parametric sweep shown in Figure 5.*

Fixed Boundary Conditions	Value
Inlet R290 Enthalpy	700 kJ/kg
Inlet R290 Pressure	1000 kPa
Outlet Water Temperature	285 K

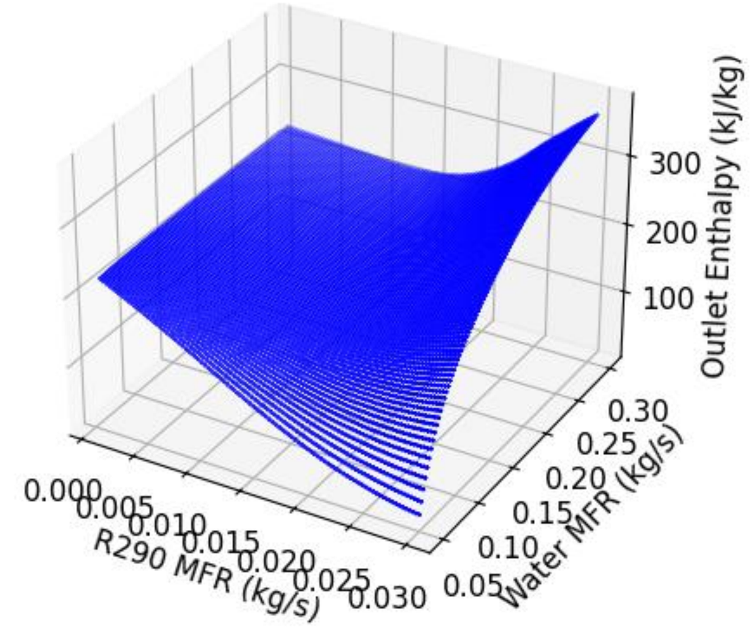

Figure 6: *Sweep of FV plate HX at different R290 and secondary mass flow rates.*

Dynamic Simulation

With proper initialization, the vapor compression cycle can be easily simulated in open loop. As an example, a four-component vapor compression cycle simulation is shown in Figure 7, where the expansion vale and compressor speed are stepped down in small increm

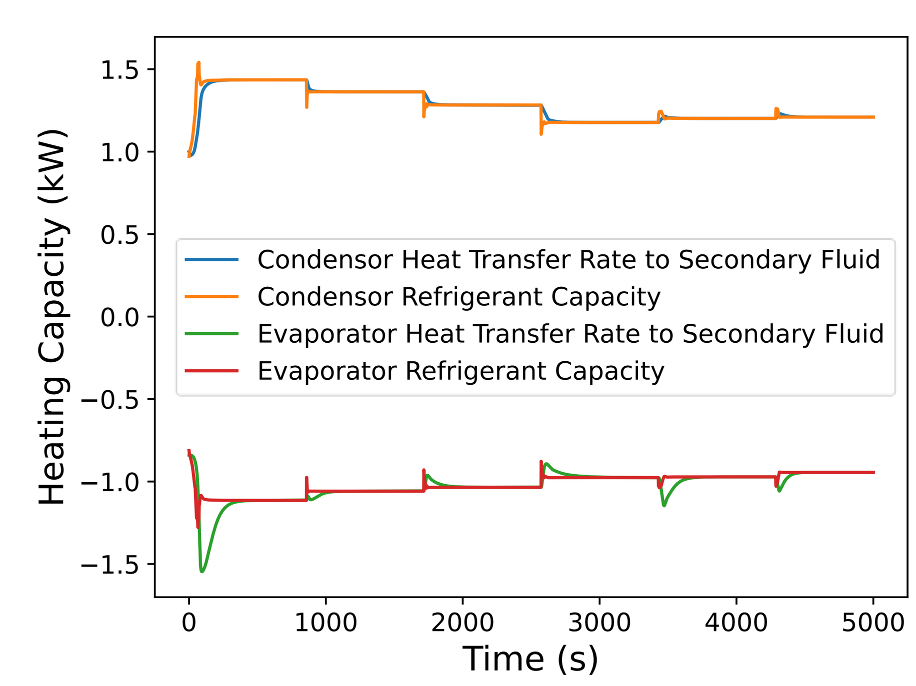

Figure 7: *Open loop simulation of a vapor compression cycle. Calculation time is 30s.*

CONCLUSIONS

- A modeling framework has been developed for the proposed multifunctional system that balances computational speed with programmatic flexibility.
- Robust numerical methods have been developed to ensure realistic dynamic simulation of a vapor compression cycle.
- Numerical results show that the proposed modeling and software framework can efficiently and robustly solve root finding and simulation tasks related to refrigerant cycles.
- Next steps include building the entire proposed system with all operating modes and constructing a co-design optimization problem to optimally select system and controller parameters.