Modeling Refrigeration Systems with Simscape Fluids

Team Member

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INTRODUCTION

Background

Refrigeration systems are essential in various applications, from domestic appliances to industrial processes. Modeling these systems accurately is crucial for design, optimization, and performance evaluation. Simscape Fluids, a MATLAB tool, provides a comprehensive environment to simulate fluid systems, including refrigeration cycles.

Objectives

To create a closed-loop refrigeration system with the goal of keeping a thermal mass within a certain temperature range for a prescribed heat load. Our specific objective is to build a refrigeration system which can maintain a 10 kg aluminium cold plate at 5^{o}C. This cold plate will be attached to a heat source with a nominal value of 1 kW. The system needs to be able to operate between environmental temperatures of 15^{o}C and 40^{o}C.

Simulation Tools

Simscape Fluids offers a platform for modeling and simulating fluid power systems, allowing for the integration of mechanical, electrical, and thermal components.

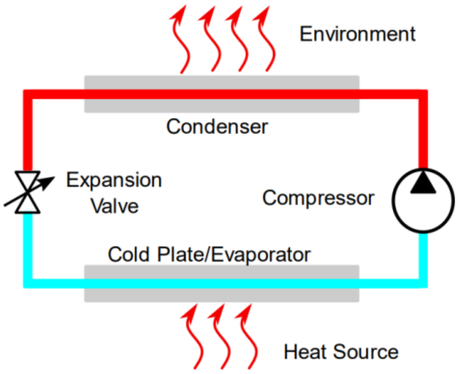


Figure 1: System model overview

System Components Overview

- The evaporator is a device which conveys heat to a refrigerant at low temperature, pressure, and quality to vaporize it. The refrigerant typically enters the evaporator in a vapor-liquid equilibrium state and leaves it as a super-heated vapor.

- The compressor heats the cold, evaporated fluid, pressurizes and transports it to the condenser side where the fluid can give up its heat to the environment. The refrigerant enters and leaves the compressor as super-heated vapor. The compressor we will model will be capable of running at different speeds and will have a flow rate that depends on the operating speed and the pressure ratio between the condenser and evaporator.

- The condenser is a device that allows the high-pressure refrigerant to phase change to liquid by exchanging heat to another cooler stream. The refrigerant enters the condenser as a super-heated vapor and exits as a sub-cooled liquid.
- The expansion valve regulates the mass flow and pressure difference between the condenser and evaporator. The refrigerant enters the valve as a sub-cooled liquid and exits in a vapor-liquid equilibrium state. The expansion valve opening is typically controlled to maintain a slightly super-heated vapor at the evaporator exit.

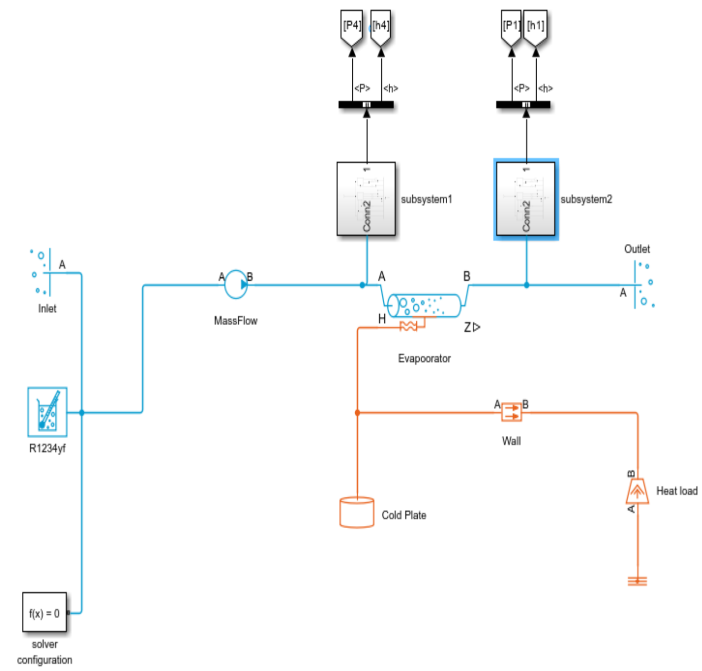
Working Fluid

We will use R-1234yf for the refrigerant, which is commonly used in automotive applications for systems within our range of temperatures. The pressure enthalpy diagram for this fluid is shown in Figure 2. From this diagram we can see the refrigerant has vapor-liquid states for temperatures above our maximum expected environmental temperature of 40°C (315.15 K), which will allow the condenser to operate properly below its critical point.

Modelling Components

1. Cold Plate and Evaporator:

- A 10 kg aluminium cold plate is modelled with specified dimensions and material properties.
- An evaporator, represented by a 3-Zone Pipe (2P) block, exchanges heat with the cold plate.
- Initial and boundary conditions are set based on thermodynamic properties, ensuring a mass flow rate of approximately 0.0104 kg/s.



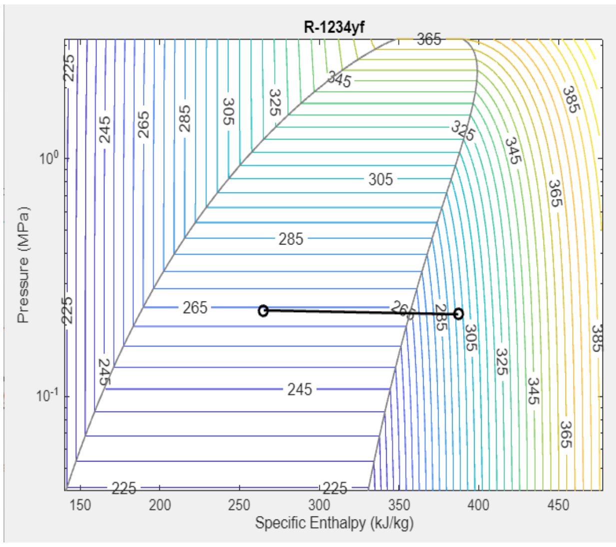
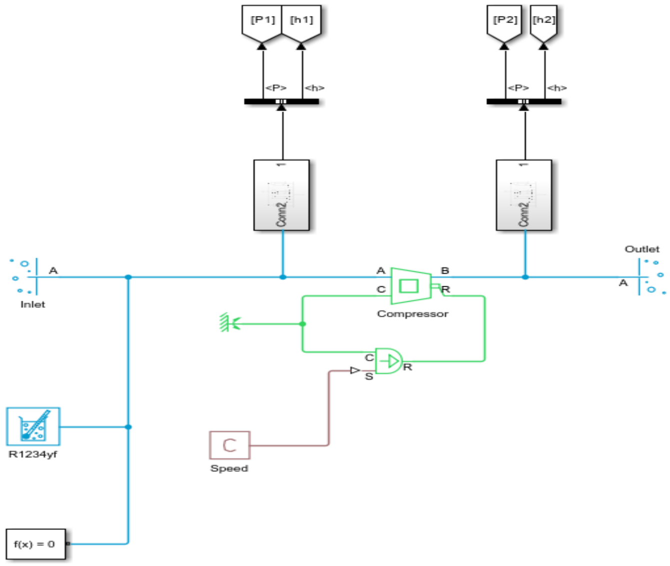


Figure 2: Test harness assembly for the evaporator/cold plate.

Figure 3: Simulation results for the evaporator/cold plate model.

2. Compressor:

- The compressor model delivers the required mass flow rate under estimated pressures.
- It operates with a PI controller to maintain the cold plate temperature.



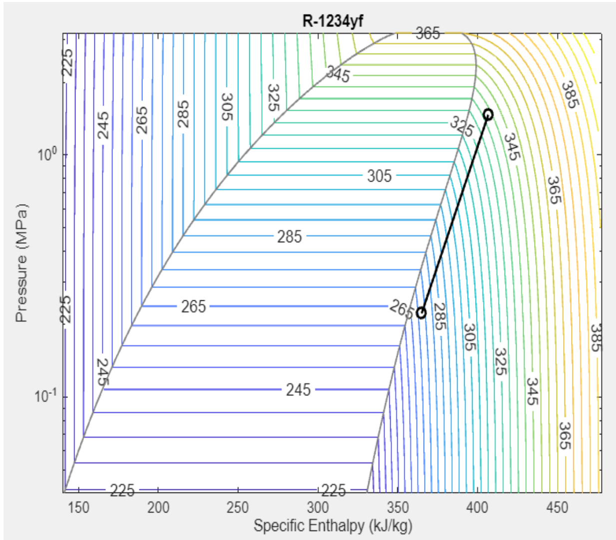
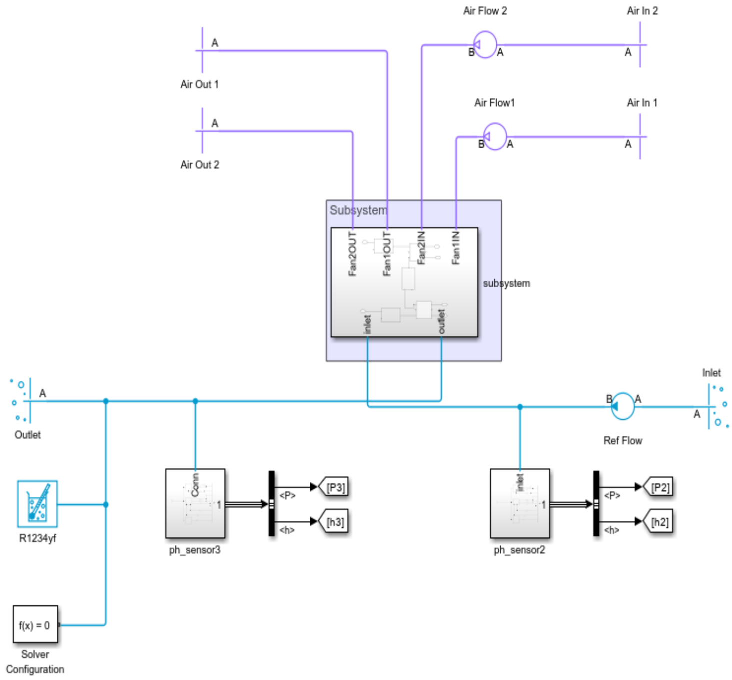


Figure 5: Pressure-enthalpy diagram for the compressor under nominal operating conditions.

Figure 4: Compressor test harness model. This model has been set up so we can vary the inlet and outlet fluid states and the rotational speed.

3. Condenser:

- Allows phase change of refrigerant by exchanging heat with moist air.
- Modelled with specific parameters to ensure efficient heat transfer.



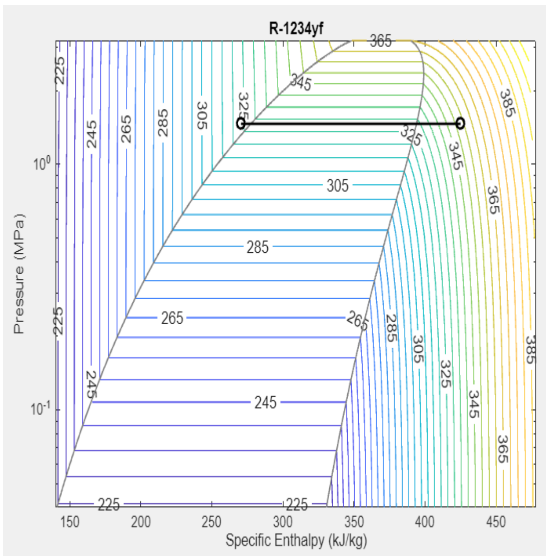
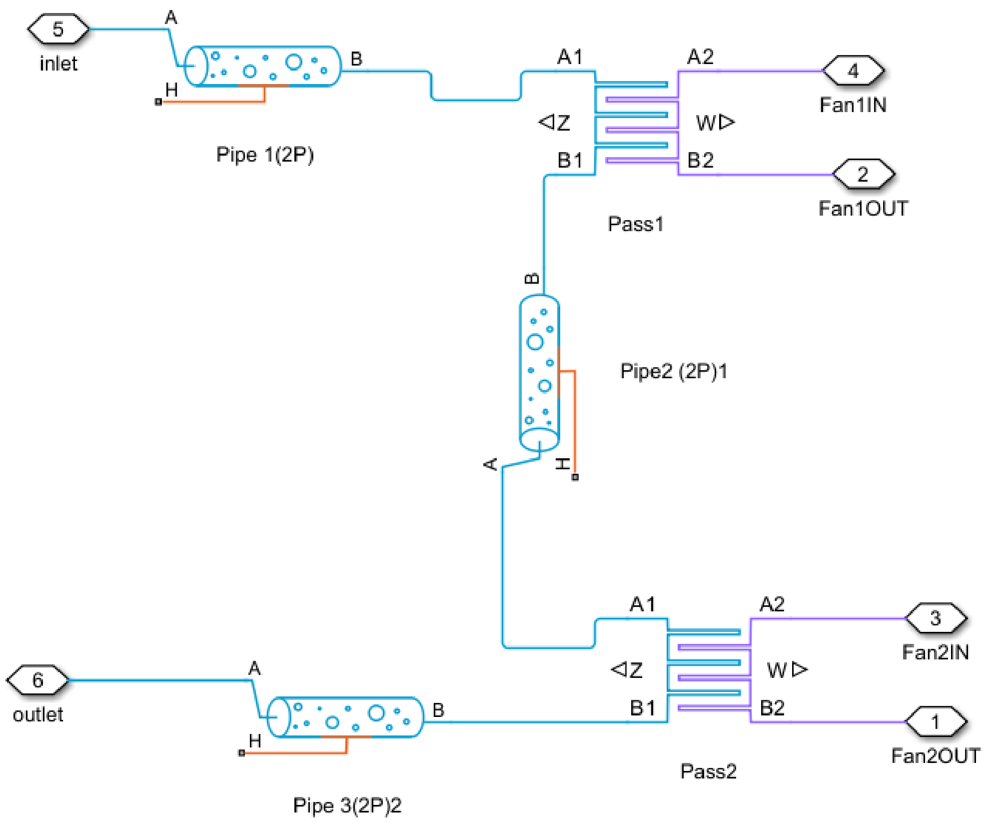


Figure 6: Test harness assembly for the condenser

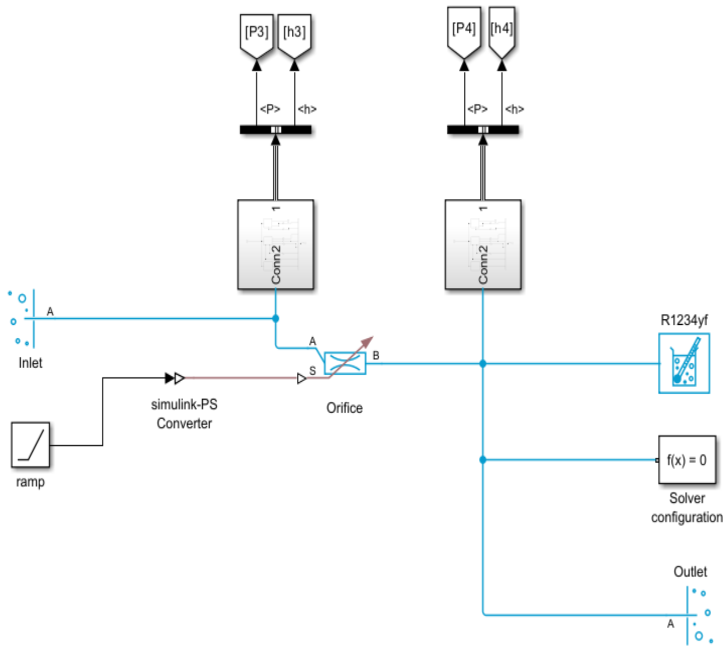
Figure 7: Simulation results for the condenser model



Subsystem of condensor

4. Expansion Valve:

- Regulates mass flow and maintains vapor-liquid equilibrium state at the evaporator exit.
- Controlled by a PI controller to adjust the valve's cross-sectional area based on the evaporator exit state.



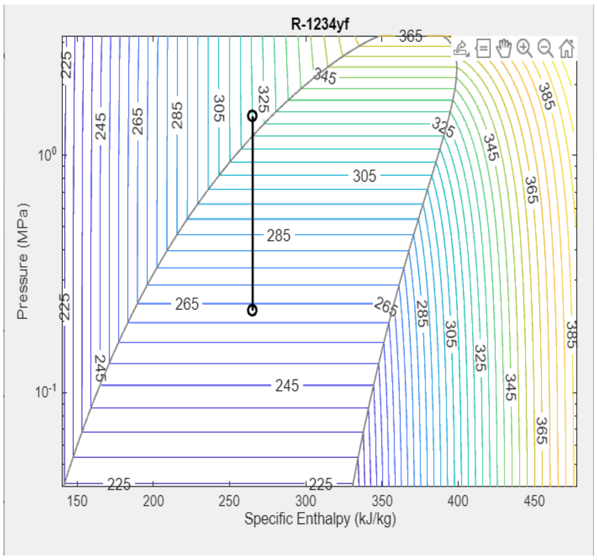


Figure 8: Test harness assembly for the Expansion Valve.

Figure 9: Simulation results for the Expansion valve model

•Closing the loop:

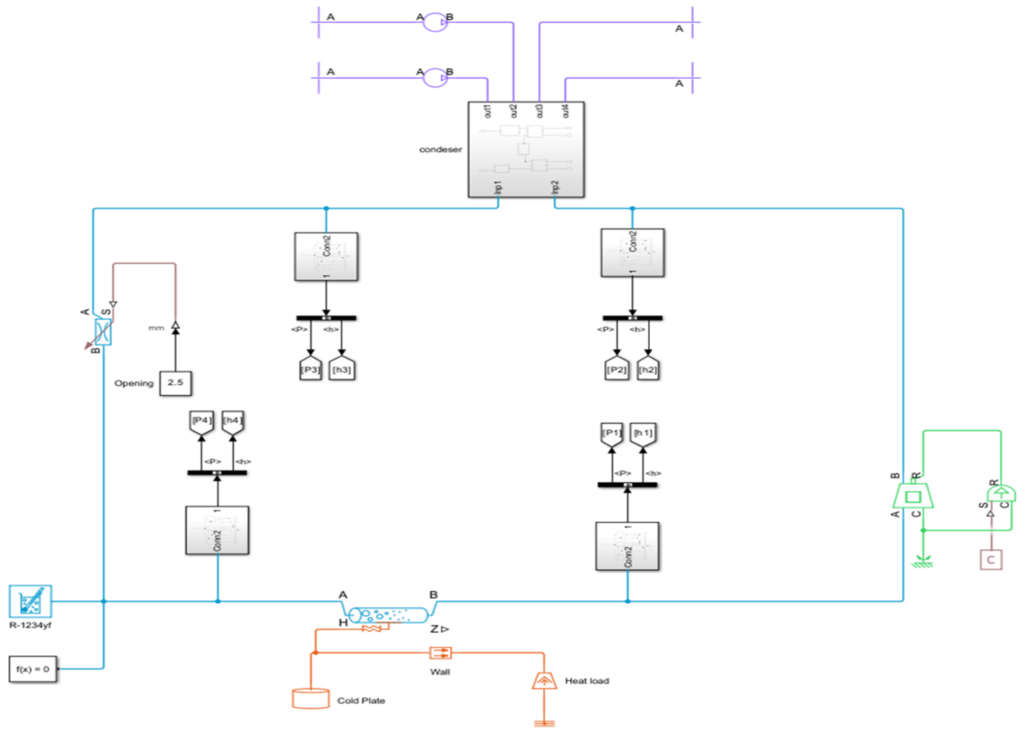


Figure 10: Test harness assembly for the closed loop refrigeration system

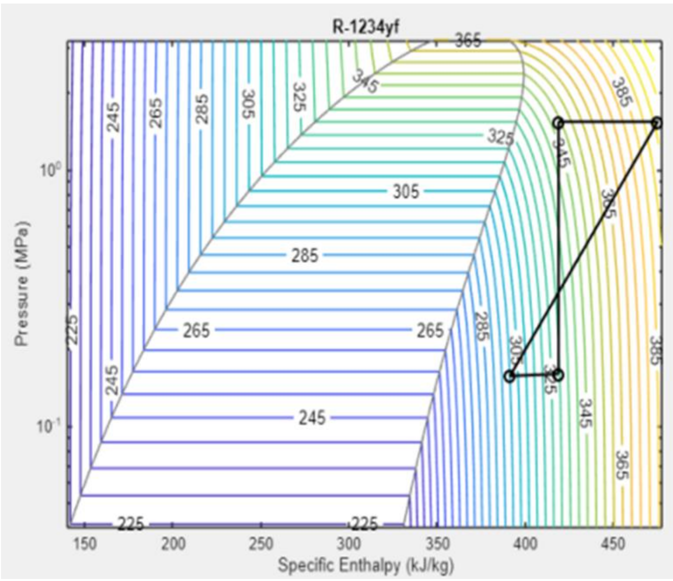


Figure 11: Closed loop p/h diagram from our first attempt. The plot indicates one of the sensors in the system is running off the fluid property

Reason for undercharging:

- The simulation quickly diverges and fails around 0.8 seconds.
- Error message indicates that the maximum valid specific internal energy has been exceeded for parts of the system.
- The p/h diagram before failure (Figure 11) shows that one of the sensors is running off the fluid property.
- Root cause: The issue is not due to component sizing but rather the definition of initial conditions.
- The system is severely undercharged with refrigerant.

- A real system in this state would rapidly overheat and fail catastrophically.

Charging the System

To understand the simulation failure, we first need to take account of the total system volume and amount of refrigerant. To do this we can set the model Stop Time to zero and simulate it. Then we can interrogate the simulation log for blocks that have internal volume nodes. These are the blocks that have will have mass in the simulation and they are:

1. Condenser manifolds – Pipe (2P)
2. Condenser heat exchangers – Condenser Evaporator (2P-MA
3. Evaporator – 3-Zone Pipe (2P)

We check the density at all above mention block , and find average of them we get 56.3 kg/m^3 . 3. A realistic value for the charge density in a R1234yf refrigerant system is about 200-300 kg/m^3, so we can conclude our system is undercharged2 .

To compute the correct system density for the system at rest in some ambient condition, we consult the property tables for the fluid. In our case, we started our system out in the worst-case environment at T=40 degree Celsius. The pressure of R1234yf under this condition can be found from a pressure/temperature table at vapor-liquid phase coexistence to be 1018.4 kPa. This gives us the initial pressure condition for the pipes and heat exchangers.

To compute the initial system quality, we can check a thermal properties database with temperature T=40 degree Celsius and density=200 kg/m^3. Alternately, we can get the vapor and liquid densities at the given temperature and interpolate. For R1234yf at 40 degrees Celsius we have a liquid density of ρl=1034 kg/m^3 and a vapor density of ρv=57.75 kg/m^3. To compute the vapor quality required to achieve our target density of ρref=200 kg/m we can use the following equation and solve for x0 which is our vapor quality

$$\rho_{ref} = \frac{1}{\dfrac{x_0}{\rho_v} + \dfrac{1 - x_0}{\rho_l}},$$

When we set the initial conditions for the properly charged system and run it, we can see that the system stabilizes to a good place that reflects our design so far. The steady-state cycle is shown in Figure 12. The condenser provides fully condensed refrigerant, and the evaporator is providing super-heated vapor to the compressor.

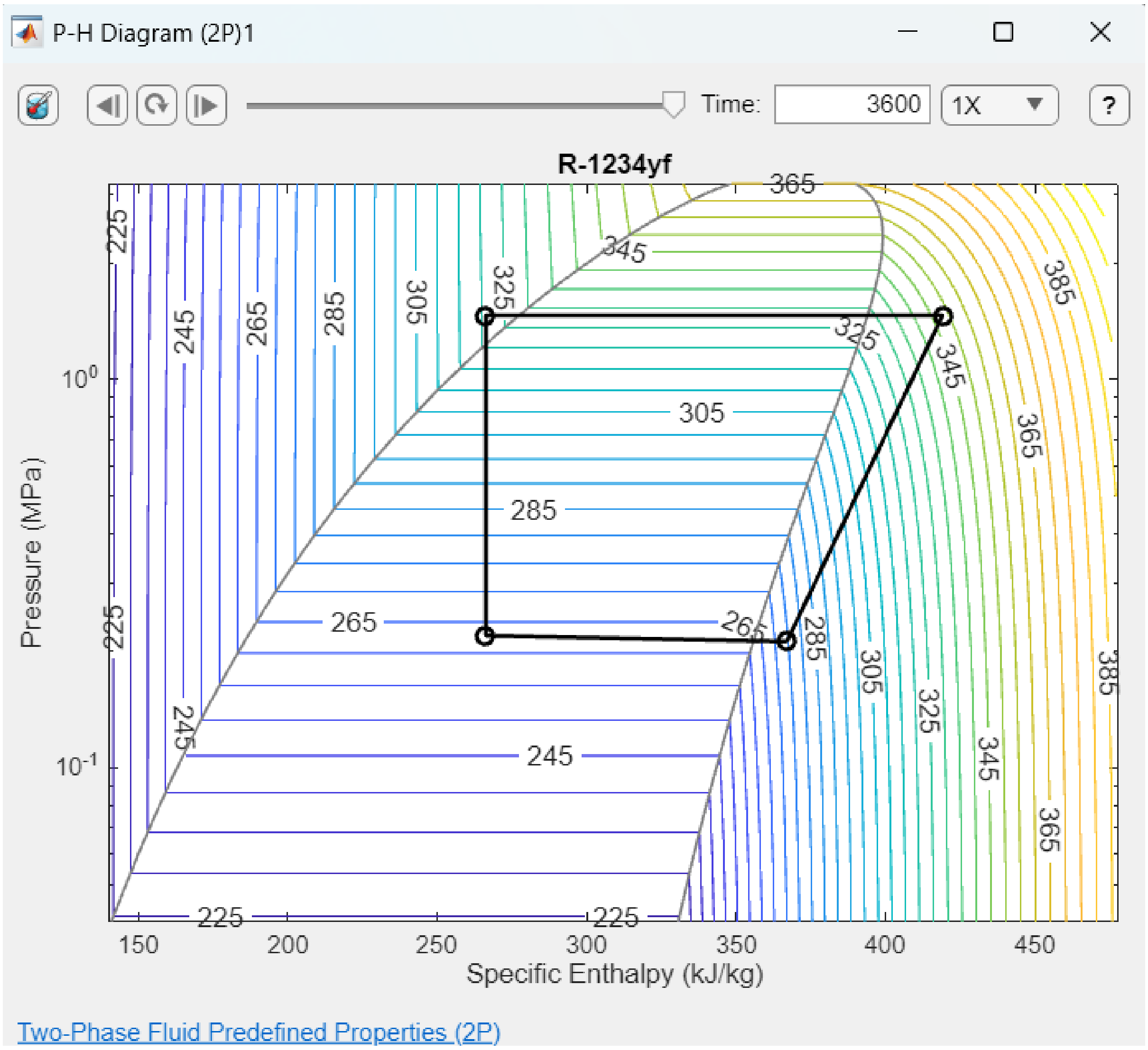


Figure 12: Thermodynamic cycle for correctly charged closed-loop system

Adding Controllers to the Model

The final stage in creating our model involves adding the rudimentary controllers to the expansion valve and compressor. The former controller will regulate the state of the fluid at the outlet of the evaporator and the latter will regulate the mass flow of the refrigerant. The combination of these two controllers will allow us to keep our cold plate at the required temperature.

Expansion Valve Control

1. System Setup:

- The system is now closed, with appropriate initial conditions and capacitance set.
- The goal is to control the expansion valve to ensure the fluid at the evaporator outlet is superheated by about 5°C using a PI controller.

2. Adding Sensors:

-Saturation Properties Sensor (2P)

- Location: Between the outlet of the expansion valve and the inlet of the evaporator.
- Purpose: Determines the saturation temperatures.

Thermodynamic Properties Sensor (2P)

- Location: Between the evaporator outlet and the compressor inlet.
- Purpose: Measures the temperature.

3. Superheat Calculation:

- Subtract the saturation temperature at the evaporator inlet from the measured temperature at the evaporator outlet.
- The calculated superheat is converted to a Simulink signal and passed through a Transfer Function with a 1 ms delay.

4. PI Controller:

- The superheat difference is compared with the desired superheat setting.
- The difference serves as input to a PI controller.
- The PI controller adjusts the valve opening: Closing the valve increases superheat by reducing fluid entry to the evaporator.

5. Compressor Control:

Temperature Sensor:

- Location: On the cold plate.
- Purpose: Assists in controlling refrigerant flow based on the cold plate's temperature.

-2-Port Constant Volume Chamber (2P):

- Location: At the compressor inlet.
- Purpose: Adds capacitance to account for compressor dynamics.

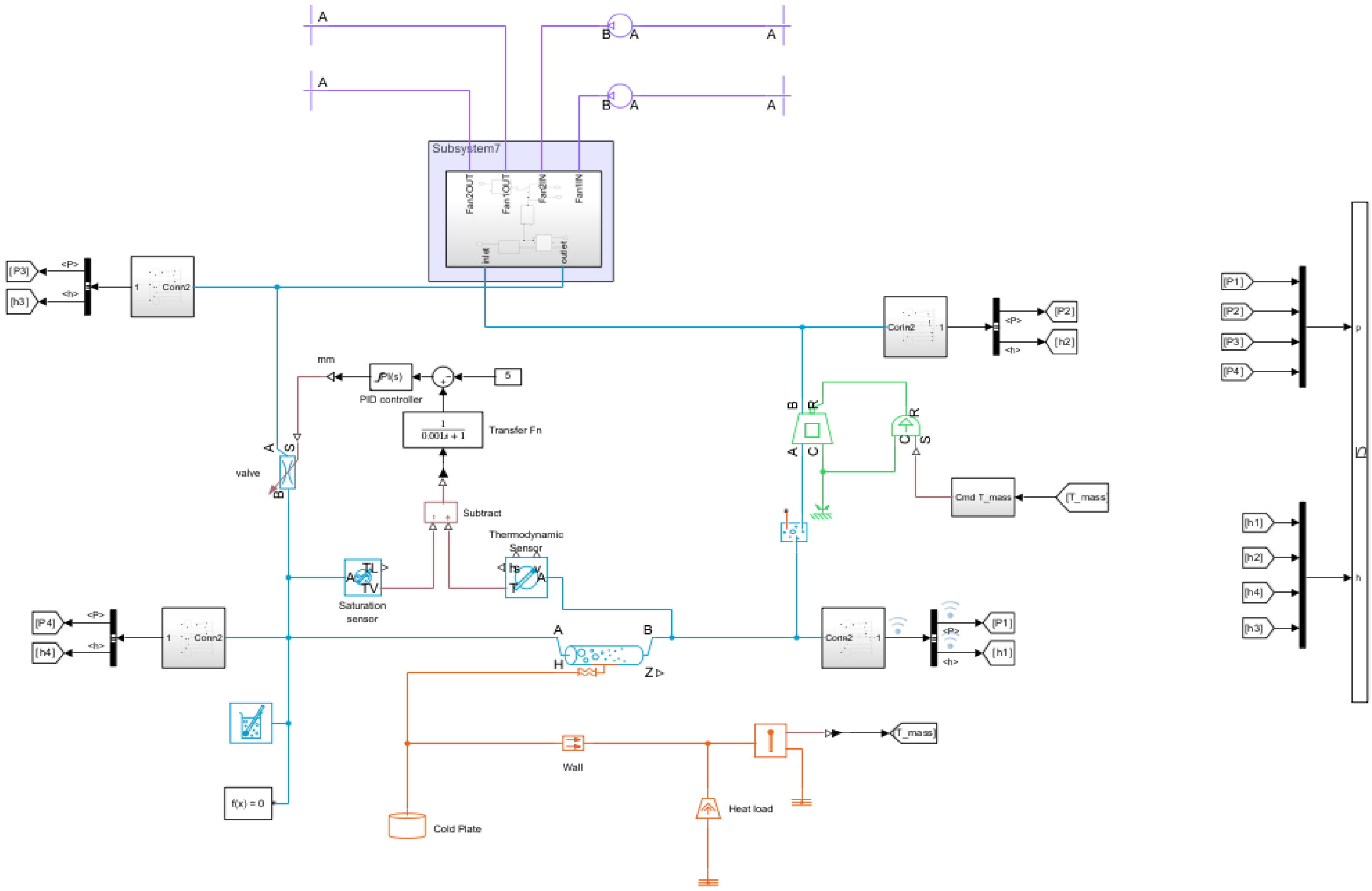


Figure 13: The finial System With controllers

Result

Once we have our model completed, we can run it and see the pressure/enthalpy diagram change dynamically as the simulation runs. In addition, we can check to see our requirement is met from the temperature measurement of the cold plate surface. This temperature is plotted in Figure 14. As can be seen there, the plate heats to around 40 degrees Celsius but quickly moves down to the required temperature. The compressor speed is shown in Figure 15.

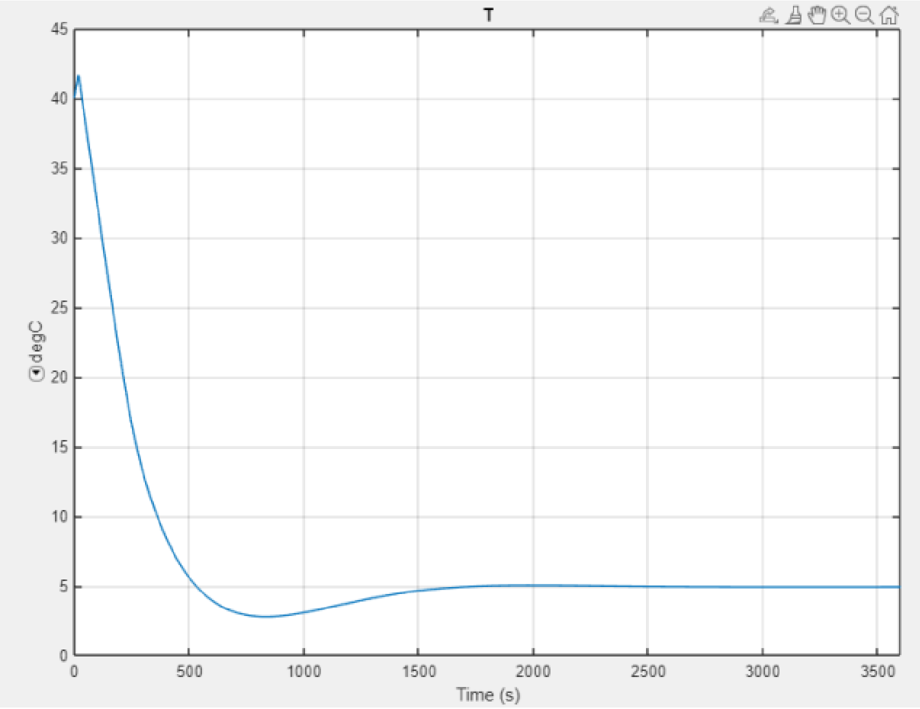


Figure 14: Cold plate temperature at full load as a function of time.

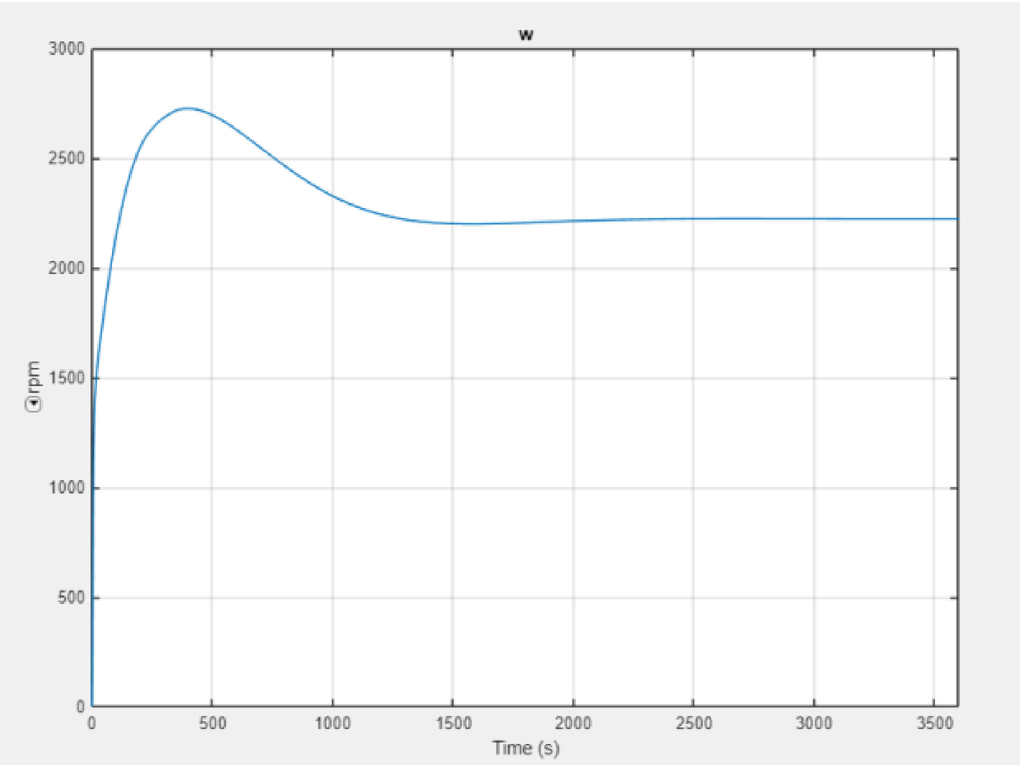


Figure 15: Compressor speed as a function of time

Conclusion

In this document, we have created a Simscape model of a simple refrigeration system for an electronics cooling application. We discussed how to start from scratch and how to select parameters for the components of the model, including the fluid properties and total fluid capacity. Next, we discussed how to ensure the system has proper initial conditions based on charge density. Finally, we added simple controllers to the model to demonstrate how to achieve goals within the model, i.e., evaporator superheat temperature and cold plate surface temperature.