Albatross Energetics

Team 53

Inter IIT Tech Meet 13.0

1 Introduction

A Vapor Compression Refrigeration system (VCRS) consists of four main components. The *Evaporator* is responsible for collecting heat from the refrigerated space in order to cool it and maintain it at a cold temperature. The *Compressor* then sucks the heated refrigerant out from the evaporator and compresses it, increasing its temperature to above ambient temperature. The *Condenser* then once again cools the refrigerant by rejecting heat to the ambient. Finally, expansion takes place in the *Expansion Valve* to reduce pressure and return the refrigerant to its initial state.

2 Working Model

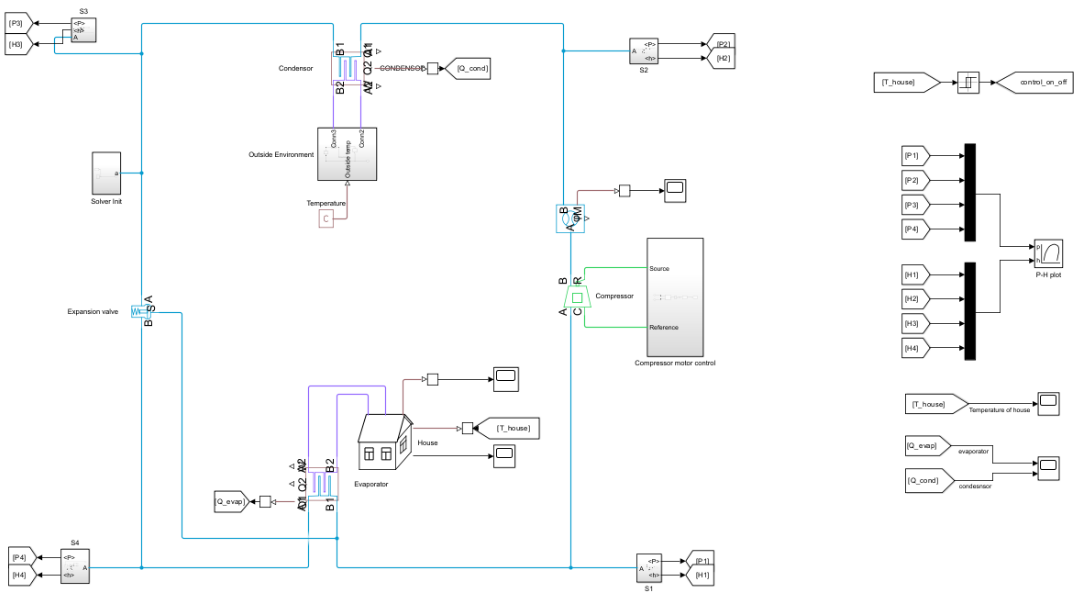


Figure 1: Simulink Model

Operating Conditions

The indoor set point is given as 27°C dry bulb temperature and 19°C wet bulb temperature. Outdoor conditions are varying with time with a maximum temperature of 43°C and a minimum of 24°C. To allow for adequate heat transfer in the evaporator and condenser, we take the evaporator temperature $T_e = 0°C$ and condenser temperature $T_c = 55°C$.

Superheating is done at the evaporator exit to ensure that no water droplets enter the compressor and damage the blades. We provide a superheat of 10K in our cycle.

From the property table for R1234yf, we get the saturated liquid and vapour properties at $T_e = 0°C$ and $T_c = 50°C$. From these, we get $P_e = 202.655$ kPa and $P_c = 1519.1$ kPa.

Evaporator

The evaporator has a dual function of both cooling and dehumidifying the ambient air in order to maintain comfort. The refrigerant goes from a two-phase mixture to superheated vapour.

Table 1: Evaporator Input Parameters

Parameters	**Values**
Flow Arrangement	Counter-Flow
Mass Flow Rate (2P)	0.01 kg/s
Inlet Pressure (2P)	0.20265 MPa
Inlet Condition (2P)	specific enthalpy
Inlet Specific Enthalpy (2P)	276.92 kJ/kg
Outlet condition (2P)	Outlet Condition
Outlet Condition Specification	Specific Enthalpy
Nominal Outlet Specific Enthalpy	372.729 kJ/kg
Mass Flow Rate (MA)	0.05 Kg/s
Inlet Pressure (MA)	101.325 kPa
Inlet Temperature (MA)	297K

Evaporator Dimensions

Heat transfer in the evaporator is given by

$$\dot{Q}_e = \dot{m}_{ref} \times (h_1 - h_4) = UA\Delta T$$

$$\frac{1}{U} = \frac{1}{h_{air}} + \frac{1}{h_{ref}} + \frac{t}{k_{Cu}}$$

$$A = A_b + \eta_f A_f$$

$$\Delta T = \frac{(T_{c,out} - T_{air,in}) - (T_{c,in} - T_{air,out})}{ln(\frac{(T_{c,out} - T_{air,in})}{(T_{c,in} - T_{air,out})})}$$

Now, $\dot{Q}_e = \dot{m}_{ref} \times (h_1 - h_4) = 0.5825$kW

putting $h_{air} = 25W/m^2 - K, h_{ref} = 1000W/m^2 - K, t = 2mm, k_{Cu} = 385W/m - K$, we get $U = 24.38W/m^2 - K$

Also, $\Delta T = 15.23K$ so we get $A = \frac{582.5}{24.38 \times 15.23} = 1.56m^2$

Considering tube outer diameter to be $d = 12$mm, length $L = 1$m and number of tubes, $n = 20$, we get $A_b = n \times \pi \times d \times L = 20 \times \pi \times 0.012 \times 1 = 0.753m^2$.

Thus, fin area, $A_f = \frac{A - A_b}{\eta_f} = \frac{1.56 - 0.753}{0.75} = 1.1m^2$.

Compressor

The compressor increases the refrigerant temperature to above ambient temperature by increasing its pressure. We used a *Positive Displacement Compressor* for our compressor model and parameterized it as follows.

$$\text{L/rev} = \frac{\text{Flow Rate (L/s)}}{\text{Revolutions per second (rev/s)}}$$

Given:

- Flow Rate (Q) = 2.2 L/s
- Frequency (f) = 50 Hz (assume this is the compressor's rotation frequency)

The frequency in Hz represents revolutions per second (1 Hz = 1 rev/s). Therefore, at 50 Hz:

$$\text{Revolutions per second} = 50 \text{ rev/s}$$

Calculation:

$$\text{L/rev} = \frac{2.2 \text{ L/s}}{50 \text{ rev/s}}$$

$$\text{L/rev} = 0.044 \text{ L/rev}$$

Table 2: Compressor Input Parameters

Parameters	**Values**
Displacement Volume	0.044 L/rev
Isentropic Efficiency	64.8%
Nominal Evaporator Superheat	10K
Nominal Volumetric Efficiency	95%
Nominal Pressure Ratio	7.5
Inlet Pressure	0.20265 MPa
Inlet Temperature	273K
Mechanical Efficiency	92%
Inlet Area	2.85 cm^2
Outlet Area	1.27 cm^2

Condenser

In the condenser, the refrigerant goes from a superheated vapour to a subcooled liquid by rejecting heat to the ambient. We used a *System Level Evaporator Condenser (2P)* to model our condenser. Refrigerant from the compressor flows in through port A1 and flows out through port B1. Moist air (surrounding air) flows in through port A2 and leaves through port B2.

Condenser Dimensions

Heat transfer in condenser is given by

$$\dot{Q}_c = \dot{m}_{ref} \times (h_2 - h_3) = UA\Delta T$$

$$\frac{1}{U} = \frac{1}{h_{air}} + \frac{1}{h_{ref}} + \frac{t}{k_{Cu}}$$

$$A = A_b + \eta_f A_f$$

$$\Delta T = \frac{(T_{c,out} - T_{air,in}) - (T_{c,in} - T_{air,out})}{ln(\frac{(T_{c,out}-T_{air,in})}{(T_{c,in}-T_{air,out})})}$$

Now, $\dot{Q}_c = \dot{m}_{ref} \times (h_2 - h_3) = 1.315$kW

putting ,$h_{air} = 25W/m^2 - K, h_{ref} = 1000W/m^2 - K, t = 2mm, k_{Cu} = 385W/m - K$, we get $U = 24.38W/m^2 - K$

Also, $\Delta T = 13.44K$ so we get $A = \frac{1315}{24.38\times13.44} = 4.01m^2$

Considering tube outer diameter to be $d = 12$mm, length $L = 1$m and number of tubes, $n = 20$, we get $A_b = n \times \pi \times d \times L = 20 \times \pi \times 0.012 \times 1 = 0.753m^2$.

Thus, fin area, $A_f = \frac{A-A_b}{\eta_f} = \frac{4.01-0.753}{0.75} = 4.34m^2$.

Table 3: Condenser Input Parameters

Parameters	**Values**
Flow Arrangement	Counter-Flow
Mass Flow Rate (2P)	0.01 kg/s
Inlet Pressure (2P)	1.5199 MPa
Inlet Condition (2P)	specific enthalpy
Inlet Specific Enthalpy (2P)	414 kJ/kg
Outlet condition (2P)	Outlet Condition
Outlet Condition Specification	Specific Enthalpy
Nominal Outlet Specific Enthalpy	267.92 kJ/kg
Mass Flow Rate (MA)	0.5 Kg/s
Inlet Pressure (MA)	101.325 kPa
Inlet Temperature (MA)	308 K

Expansion Valve

An Expansion device is used to expand the liquid from condenser pressure to evaporator pressure in order to bring it back to its original state. We used a *Thermostatic Expansion Valve (2P)* to model our expansion device. Thermodynamically, enthalpy before throttling is same as enthalpy after throttlings, i.e. $h_3 = h_4$.

3 Assumptions

Modeling the actual Vapour Compression Refrigeration Cycle will be difficult, resource-intensive, and time-consuming. So, certain simplifications were made in order to make the model simpler to run.

Table 4: Thermostatic Expansion Valve Input Parameters

Parameters	Values
Capacity Specification	Evaporator Heat Transfer
Nominal Evaporator Heat Transfer	0.6 kW
Maximum Evaporator Heat Transfer	1.5 kW
Nominal Pressure Specification	Specific pressure
Nominal Condenser Outlet Pressure	1.5199 MPa
Nominal Evaporator Outlet Pressure	0.20265 MPa
Nominal Condenser Subcooling	0K
Nominal (static + opening) Evaporator Superheat	10K
Static (minimum) Evaporator Superheat	0K

- **Condenser and Evaporator**:We used the *System Level Condenser Evaporator (2P)* block instead of the *Condenser Evaporator (2P)* block to model the condenser and the evaporator. The system-level block does not require the exact dimensions (length of pipe, number of fins, fin dimensions, pipe diameter and thickness, etc.) of the heat exchanger, but we can model them by specifying the inlet and outlet conditions. This simplifies the calculation because the evaporator has to both cool and dehumidify the room, so it will be a case of heat transfer through wetted fins.
- **Simplified House Thermal System**: At any time, the indoor temperature will not be equal to the ambient temperature because of thermal resistance provided by the walls, windows, and roof. So, we assumed a simplified thermal network for heat transfer from ambient to interior. This considers convection from ambient air to exterior wall, conduction from exterior surface of wall to interior surface, and then convection from interior surface of the wall to interior air

4 Performance Metrics

Room Temperature

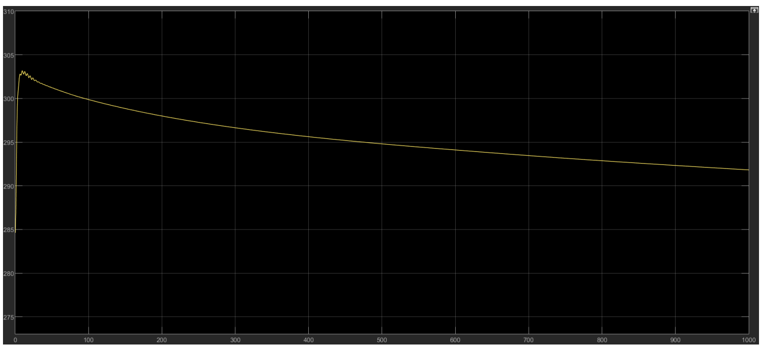


Figure 2: Room Temperature

Coefficient of Performance

Coefficient of Performance of a cycle is defined as the ratio of the amount of cooling provided to the work provided to the compressor, i.e. $COP = \frac{\dot{Q}_e}{\dot{W}_c}$. It gives us an idea of the performance of the system. Higher COP means that we need less compressor work for a particular cooling load, so running cost decreases.

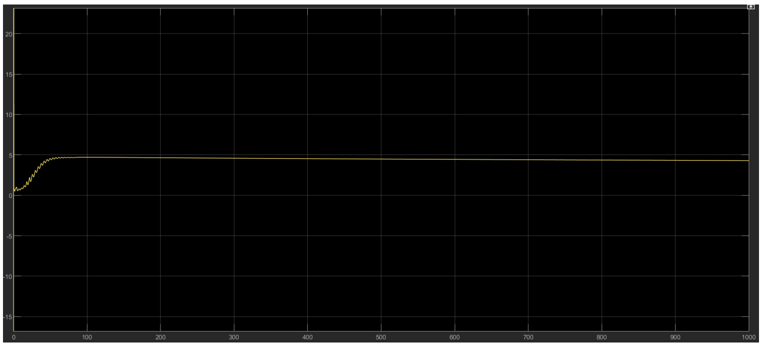


Figure 3: Coefficient of Performance

Energy Efficiency Rating

The energy efficiency ratio (EER) is the ratio of the cooling capacity in British thermal units (Btu) per hour to the power input in watts. A higher EER rating indicates a more efficient air conditioner. It is the same as COP, but in COP both numerator and denominator are in Watts (or kW). Here the numerator and denominator have different units. To convert from COP to EER, we can use the conversion factor as follows:

$$EER = 3.4124 \times COP$$

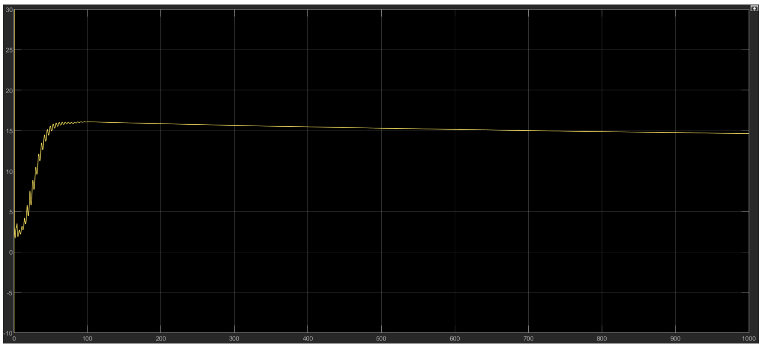


Figure 4: Energy Efficiency Rating

Room Temperature

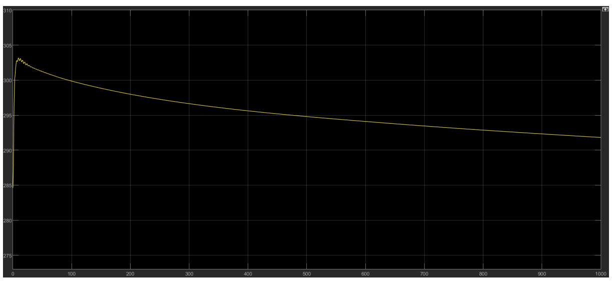


Figure 5: Room Temperature

Cooling Delivered and Power Consumption

$$\dot{W}_{comp} = \dot{m}_{ref} \times (h_2 - h_1)$$

$$\dot{Q}_e = \dot{m}_{ref} \times (h_1 - h_4)$$

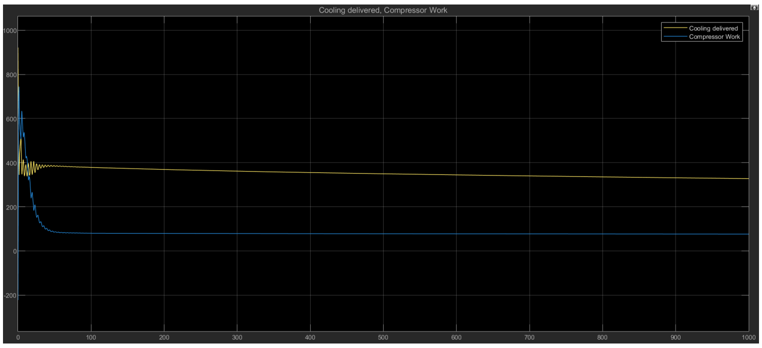
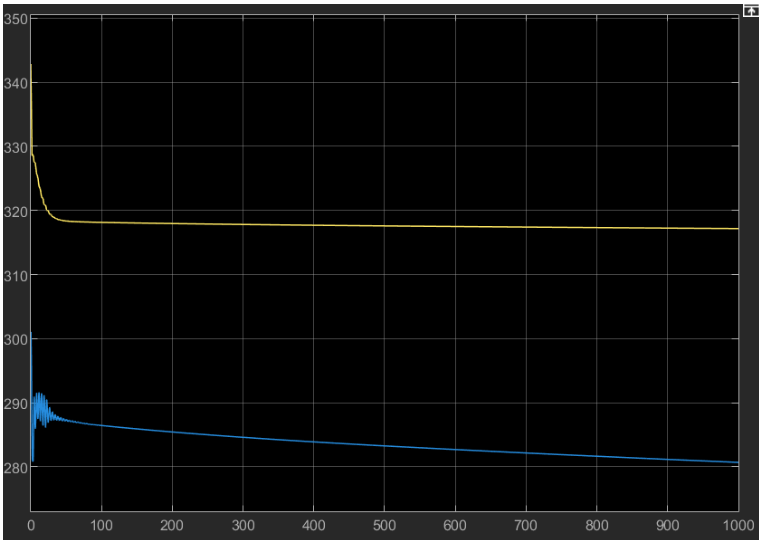
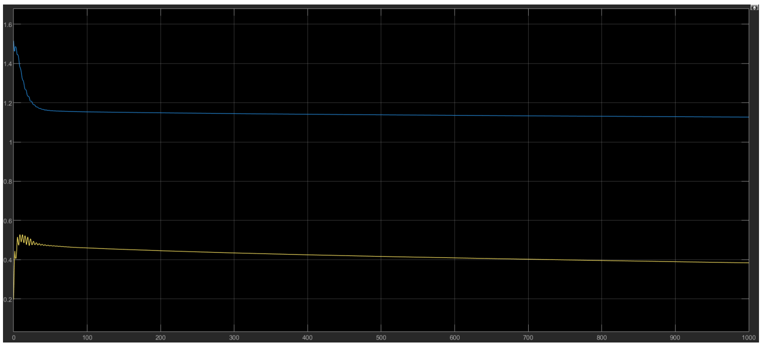


Figure 6: Cooling Delivered and Power Consumption

Condenser and Evaporator Pressures and Saturation Temperatures



(a) Temperature (Evaporator in blue, Condenser in yellow)



(b) Pressures (Evaporator in yellow, Condenser in blue)

Figure 7: Condenser and Evaporator Temperature(K) and Pressures(MPa)

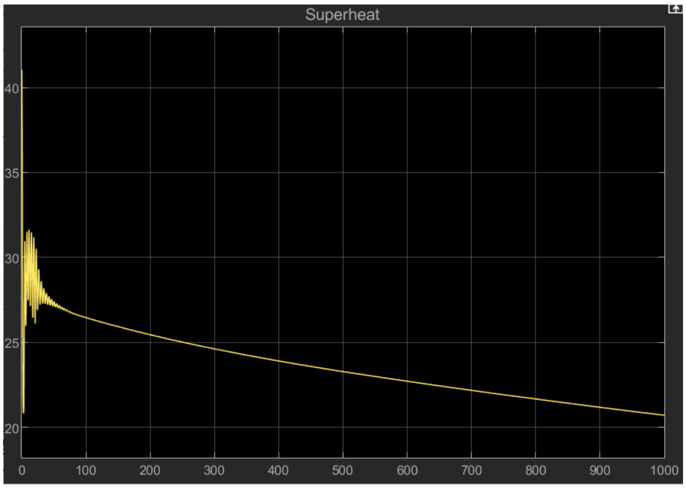


Figure 8: Superheating

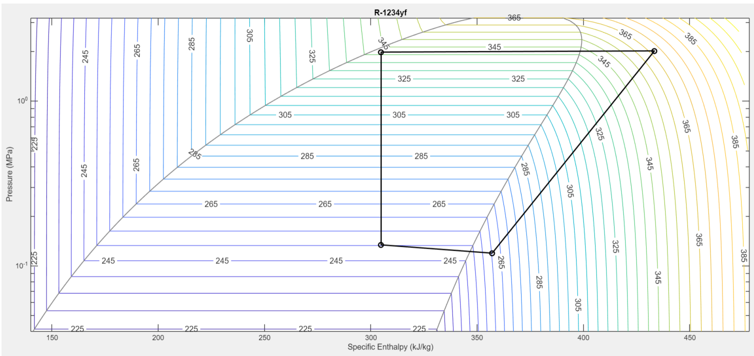


Figure 9: P-h plot

Superheating

P-h Plot

5 Key Innovations and Environmental Considerations

Refrigerant Choice

The choice of refrigerant is very important in any refrigerating system. Choosing the correct one will provide an optimum balance of performance and environmental impact. Favourable characteristics for a refrigerant in a VCRS are:

- **Low liquid specific heat $(C_p)_f$:** Reduces the throttling loss. It also reduces the dryness fraction at evaporator inlet, which improves the heat transfer and reduces pressure drop in the evaporator.
- **High vapor specific heat $(C_p)_v$:** Reduces the superheat loss. It also allows us to provide less superheat, which keeps the compressor exit temperature low.
- **High critical temperature T_c and normal boiling point (NBP):** Ensures that the condenser is operating far away from the critical point, so that the de-superheating zone decreases and constant temperature heat rejection zone increases, leading to less irreversibilities.
- **Low Global Warming Potential (GWP) and Ozone Depletion Potential (ODP)**: One of the most important aspects is that global warming and ozone layer depletion must

be kept in control. Using a refrigerant that provides high performance but also damages the environment is not viable in the long run.

- **Non-toxic & non-corrosive:** Choice of refrigerant must be done after taking into consideration pipe material. For example, Ammonia cannot be used with Copper tubes in heat exchanger.

Table 5: Refrigerant Properties

Refrigerant	**GWP**	**NBP (°C)**	**Critical temperature (°C)**	$(C_p)_f$ **(kJ/kg-K)**	$(C_p)_v$ **(kJ/kg-K)**
R290	0	-42	96.7	2.71	1.6
R134a	1430	-26.08	101.1	1.51	0.851
R407C	1774	-43.63	86.0	1.54	0.83
R450A	601	-23.40	104.5	1.403	0.8732
R454A	236	-47.8	78.9	1.622	0.884
R513A	629	-29.2	95.1	1.412	0.881
R410A	2088	-48.5	72.8	1.8	0.84
R1234yf	0	-29.4	94.7	1.392	1.053

Based on the above table, we select R1234yf as the refrigerant to be used in our cycle.

6 Cost Analysis

Initial Costs

Inital setup costs will include the cost of the heat exchangers for the condenser and evaporator, cost of the compressor, and cost of refrigerant which has to be filled inside the system.

Compressor

Initial cost of a Refrigerant Compressor for a 1.5 Ton AC in India is around Rs. 20,000.

Tubes

Condenser and Evaporator tubes are made up of Copper, and

Total length of copper tube = $n_{tubes} \times L = 40 \times 1 = 40m$

Inner diameter of each tube = 10 mm

Thickness of each tube = 2 mm

Weight of tube per metre = $\frac{\pi}{4}(d_o^2 - d_i^2) \times \rho = 0.31Kg$

Total weight = $40 \times 0.31 = 12.4Kg$

Cost of tube per Kg = Rs. 850

Total cost of copper tubes = 12.4×850=Rs.10,540.

Fins

Fins are made up of Aluminium. Total fin area = 4.34 + 1.1 = 5.44 m^2

Fin thickness = 2mm = 0.002m

Price of Aluminium per Kg = Rs. 300

Cost of fins = 0.002 × 5.44 × 2700 × 300= Rs. 8,812.

Total Setup Cost

The total setup cost of this refrigeration system is approximately, Rs 19,352.

Running Costs

Compressor Work = 0.733kW

Considering that the AC runs for 12 hours per day, total energy consumption per day = 0.733 × 12 = 8.796kWh. Cost of 1kWh electricity in India is approximately Rs. 9.

So, total cost per day = 8.796 × 9 = Rs.79

Total cost per year = 79 × 365=Rs.30,000.

6.1 Complex House Thermal Model

We also tested our model with a more complex thermal model for the room, as shown in figure 7. The subsystem required higher flow rates , around 0.2 to 0.6 Kg/s. Our current compressor, the scroll 2, provides around 0.01 Kg/s at 860 rpm based on the volumetric displacement of 0.044 L/Revolution. Thus cooling this thermal subsystem might require a stronger compressor. While cooling with this thermal subsystem, the power load was around 5 to 10 Kw depending on the Inlet temperature. A compressor with around 10 times the volumetric displacement per revolution (0.44 L/rev) works properly with this thermal network. This value is in range of 5 Ton AC units.For 2560 Rpm, it takes nearly 200 seconds to cool down to the set point temperature. The power input for this is around 2-3 kW, which is reasonable, but not possible with the given compressor. I.E to utilize a more complex thermal subsytem for the house, as presented in Mathworks examples, we would require a much more powerful compressor, and an power input of round 2 kW.

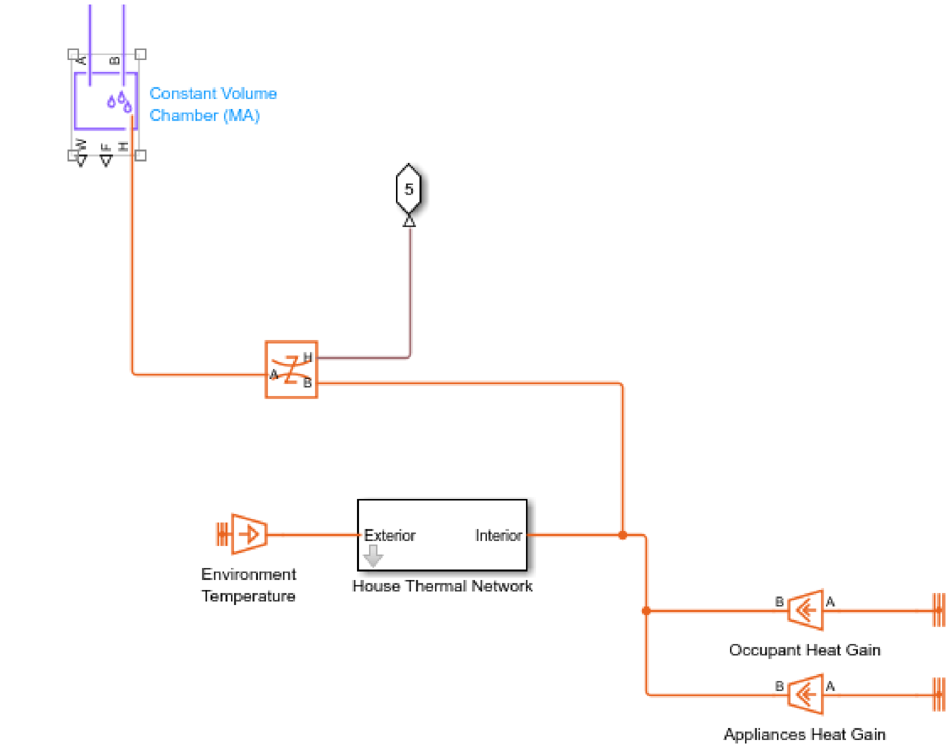


Figure 10: The more complex house thermal system

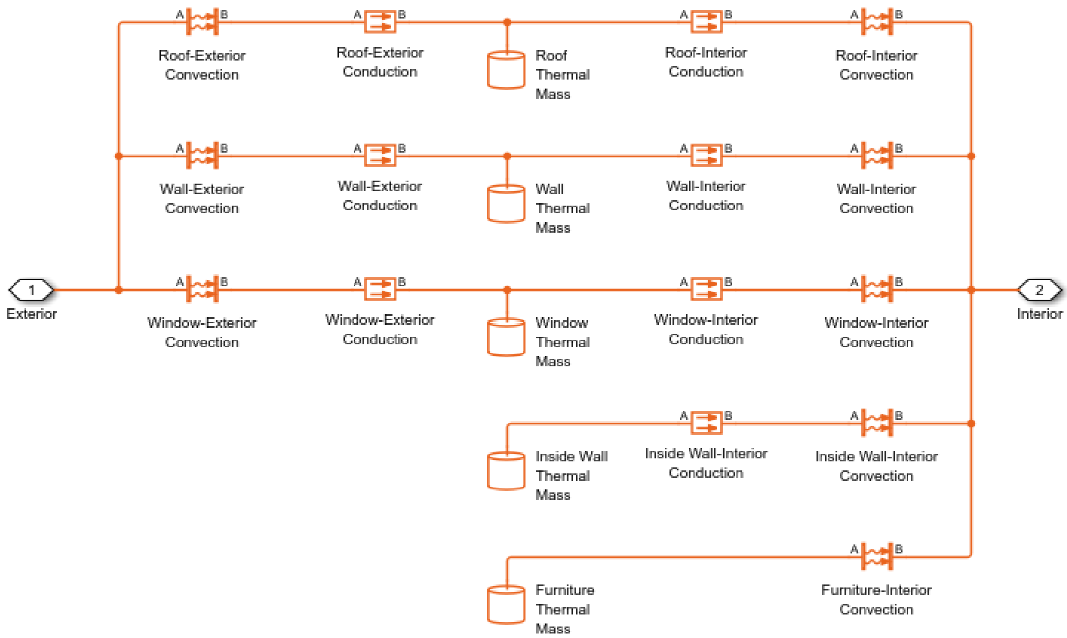


Figure 11: House Thermal Network