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Chapter 1. Cooling Loads and Refrigeration Cycle Model

Get Started

This section provides an overview of the modelling techniques and literature review used for different parts of the Simulink Model. Previous HVAC knowledge is beneficial in understanding the model.

Model Parameters

This section will go through the parameters that are available in the model and how they can be changed to fit any scenario in the model

Model Blocks

This section provides information about the different Simulink or Simscape blocks that are being used for the model.

Model Navigation

This section provides an overview on how the different parts of the model does and where to find the results from the model.

Model Control Panel

Results

This section contains the results that are obtained from the model and are subjected to change depending on the input parameters. Interpretation of the different results will depend on what input behavior is used for appliances, solar loads, occupants etc.

Chapter 2. Getting Started with Cooling Loads and Model

2.1 Methodology

All the cooling loads are divided into two categories which are the source of sensible and latent heat gains. These categories are used throughout the model for reference.

2.2 Sources of Heat Losses and Cooling Loads

A. Sensible Heat Gain

1. Heat conduction from exterior walls, floors, ceilings, doors, and windows.
2. Solar Radiation (Heat Transmitted through glass of windows, ventilators, and doors. Heat absorbed by walls and roofs exposed to Solar Radiation.
3. Heat conduction from interior unconditioned partitions or rooms.
4. Heat given off by lights, appliances, motors, machinery, and cooking operations.
5. Heat given off by residents or occupants in the room.
6. Heat carried by the infiltrated air due to leaks in through the cracks in doors, windows, and frequent openings of doors.
7. Heat gains due to walls of ducts carrying conditioned air through unconditioned space in the building.
8. Heat gain from the ceiling fan or any other fans.

B. Latent Heat Gain

1. Heat gains due to moisture in the air infiltrating the room
2. Heat gains due to condensation of moisture from occupants
3. Condensation of moisture from any process such as cooking taking place within the conditioned space
4. Heat gains due to moisture passing directly into the conditioned space through the walls or partitions inside permeable to air or from outside adjoining regions where the water vapor pressure is high.

Table 1 Categorization of Cooling Loads

Category A	
I	Direct **Heat conduction** from exterior walls, floors, ceilings, doors, windows and roof
II	**Solar Radiation** (Heat Transmitted through glass of windows, ventilators and doors. Heat absorbed by walls and roofs exposed to Solar Radiation
III	Heat conduction from **interior unconditioned partitions** or rooms.
IV	Heat given off by **lights, appliances, motors, machinery, and cooking operations**
V	Heat given off **by residents or occupants** in the room.
VI	Heat carried by the **infiltrated air** due to **leaks** in through the cracks in doors, windows, and frequent openings of doors.
VII	Heat gains due to **walls of ducts** carrying conditioned air through unconditioned space in the building
VIII	Heat gain from the **ceiling fan** or any other rotary equipment.
Category B	
I	Heat gains due to **moisture** in the **air infiltrating** the room
II	Heat gains due **to condensation of moisture from occupants**
III	Condensation of moisture from any process such as **cooking taking place within the conditioned space**
IV	Heat gains due to **moisture passing directly into the conditioned space through the walls** or partitions inside permeable to air or from outside adjoining regions where the water vapor pressure is high

Chapter 3. Further Categorization of Cooling Loads

The different loads from categories A and B will be measured either experimentally or it is to be referenced from the literature.

Table 2 Different Cooling Loads and Categories

Test Parameter	Category
Inside Design Conditions	-
Outside Design Conditions	-
Sensible heat gain from glass	A (I)
Sensible heat gain from walls	A (I)
Sensible heat gain from ceiling	A (I)
Solar heat gain from glass	A (I)
Solar heat gain from walls	A (II)
Solar heat gain from roof	A (II)
Sensible Heat from partitioned Rooms	A (III)
Equipment (Motor, Iron, etc) sensible heat gain	A (IV)
Equipment (Motor, Iron, etc) latent heat gain	B (IV)
Sensible heat gain from lights	A (IV)
Sensible load per person	A (V)
Infiltration Load	A (VI)
Sensible Heat gains from the walls of ducts	A (VII)
Sensible heat gain from fans	A (VIII)
Heat gain from moisture of infiltrated air	B (I)
Latent load per person	B (II)
Latent heat from Organics (Food or Eatables)	B (III)
Equipment (Motor, Iron, etc) latent heat gain	B (IV)

Chapter 4. Scenarios for Cooling Loads in Lab

The cooling loads for different scenarios will be estimated from the MATLAB model and they will be used for testing in the Split AC Lab. Different scenarios have been listed in **Table 3**

Table 3 Cooling Load Scenarios for Testing

I	Heat Loads
1	A (I)
2	A (I) + A (V)
3	A (I) + A (V) + A (II)
4	A (I) + A (V) + A (II) + A (IV)
5	A (I) + A (V) + A (II) + A (IV) + A (VIII)
6	A (I) + A (V) + A (II) + A (IV) + A (VIII) + A (VI)
7	A (I) + A (V) + A (II) + A (IV) + A (VIII) + A (VI) + B (I)
8	A (I) + A (V) + A (II) + A (IV) + A (VIII) + A (VI) + B (II) + B (I)

Chapter 5. Room and Environment Model

Table 4 Basic Room Dimensions

Width/Floor/Ceiling (ft)	Length (ft)	Ceiling Height (ft)	Number of Occupants	Number of Florescent Lights	Number of Computers/Laptops

5.1 Modelling and Estimate Value of A (I)

Normally, a room consists of 4 walls which may or may not have a window. So, the model should predict the heat loss through a solid concrete wall and through a combination of glass, air gap and concrete walls. The approximate thicknesses of wall and glass will be taken as variables as they can vary a lot depending on the construction. The wind speed and convection transfer will also vary the heat transfer through the walls, but they can be taken as approximate or separate complex model can be used to predict the heat transfer coefficient.

Also, as the day passes by, the temperature of the air outside the room and the convection coefficient is dynamically changing so to add this effect, a dynamically changing convection coefficient and temperatures will be used.

After having modelled the parameters, the heat transfer or heating load will be calculated and will show variable loads depending on the time of that day.

Table 5 Dimensions of Room

Wall Orientation	**Wall Area (ft^2)**	**Window Area (ft^2)**	**Door Area (ft^2)**
North			
South			
West			
East			
Roof/Ceiling/Top			
Floor/Bottom			

5.1.1 Heat Transfer Through a Solid Concrete Wall:

Heat transfer through a normal wall can be modelled as shown in **Figure 1**

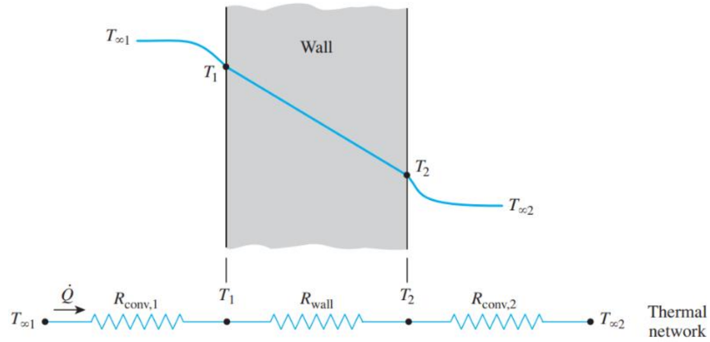


Figure 1 Thermal Network of a Normal Concrete Wall

$$h_1 = Convection\ Coefficient\ of\ Inner\ Surface$$
$$h_2 = \ Convection\ Coefficient\ of\ Outer\ Surface$$
$$k_{wall} = Thermal\ Conductivity\ of\ the\ Concrete\ Wall$$
$$T_{\infty_1} = Temperature\ of\ its\ inner\ Surface$$
$$T_{\infty_2} = Temperature\ of\ its\ Outer\ Surface$$
$$A = Heat\ Transfer\ Area$$
$$L = Thickness\ of\ the\ Wall$$
$$R_{conv} = \frac{1}{hA}$$
$$R_{wall} = \frac{L}{kA}$$
$$R_{total} = \sum R_i$$

Here, h_2 and T_{∞_2} are varying due to changing environmental condition.
We will assume that h_1 remains constant for simplicity but T_{∞_1} will also be changing during the condition where the refrigeration unit is turned on.

5.1.2 Heat Transfer Through a Multilayer Plane Wall:

In **Figure 2,** the generalized network is shown and can be replaced by any number of layers provided that the property of the material is known. This model is great in predicting the heat transfer through walls which have windows or airgaps.

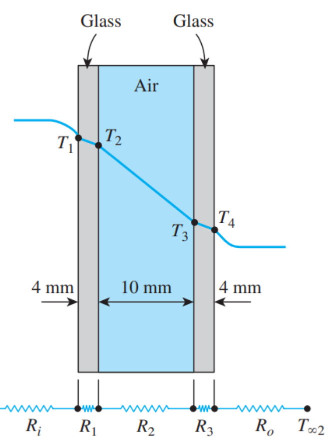


Figure 2 Thermal Network of a Multilayer Plane Wall

$$h_1 = Convection\ Coefficient\ of\ Inner\ Surface$$
$$h_2 = Convection\ Coefficient\ of\ Outer\ Surface$$
$$k_{wall} = Thermal\ Conductivity\ of\ the\ Concrete\ Wall$$
$$k_{glass} = Thermal\ Conductivity\ of\ Glass$$
$$T_{\infty_1} = Temperature\ of\ its\ inner\ Surface$$
$$T_{\infty_2} = Temperature\ of\ its\ Outer\ Surface$$
$$A = Heat\ Transfer\ Area$$
$$L = Thickness\ of\ the\ Wall$$
$$R_{conv} = \frac{1}{hA}$$
$$R_{wall} = \frac{L}{kA}$$
$$R_{total} =$$

5.2 Modelling and Estimation of A (V)

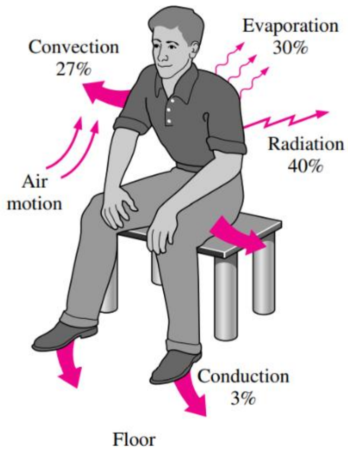


Figure 3 Average Heat loads from Human Body

5.2.1 Scenario:

Basically, in a refrigerated space, there can be a lot of occupants or residents in a room. To model the heat generated from a person we need to cater the sensible and latent of the human skin and metabolism.

The sensible heat transfer depends on the temperature of the skin and the type of clothing while the latent heat will depend on how wet the skin is ad how much moisture is added in the lungs to the air.

5.2.2 Sensible Heat Transfer from Human Body:

The overall sensible heat transfer from an occupant is basically the following:

$$\dot{Q}_{cond+conv} = \frac{A_{clothing}(T_{skin} - T_{operative})}{R_{clothing} + \frac{1}{h_{combined}}}$$

Where,

$A_{clothing} = Average\ heat\ transfer\ area\ of\ clothing$

$T_{skin} = Average\ temperature\ of\ the\ human\ skin$

$T_{operative} = Average\ of\ the\ surrounding\ and\ ambient\ temperatures = \frac{T_{ambient} + T_{surr}}{2}$

$R_{clothing} = Average\ Thermal\ Resistance\ of\ Clothing$
$h_{combined} = Combined\ Convective\ and\ Radiation\ heat\ trasnfer\ coefficient$

1. The convective heat transfer coefficient of a clothed body can be estimated from **Figure 4.**
2. The thermal resistance of trousers, long-sleeve shirt, long-sleeve sweater, and T-shirts is usually 0.155 m^2. °C/W. Summer clothing such as light slacks and short-sleeved shirt has a thermal resistance of 0.0775 m^2.°C/W. whereas winter clothing such as heavy slacks, long-sleeve shirt, and a sweater or jacket has a thermal resistance of 0.1395 m^2.°C/W
3. When the body is at thermal comfort, the skin temperature is usually 33°C $\pm$1.5°C
4. Surface area of an average man is 1.8 m^2
5. Average indoor radiation heat transfer coefficient in typical conditions is 4.7 W/m^2 °C

TABLE 16–3

Convection heat transfer coefficients for a clothed body at 1 atm *V* is in m/s) (compiled from various sources)

Activity	h_{conv}* W/m^2 · °C
Seated in air moving at	
$0 < V < 0.2$ m/s	3.1
$0.2 < V < 4$ m/s	$8.3V^{0.6}$
Walking in still air at	
$0.5 < V < 2$ m/s	$8.6V^{0.53}$
Walking on treadmill in still air at $0.5 < V <$ 2 m/s	$6.5V^{0.39}$
Standing in moving air at	
$0 < V < 0.15$ m/s	4.0
$0.15 < V < 1.5$ m/s	$14.8V^{0.69}$

*At pressures other than 1 atm, multiply by $P^{0.55}$, where *P* is in atm.

Figure 4 Heat Transfer Coefficient of a Clothed Body

5.3 Modelling and Estimate Value of A (II)

5.3.1 Solar Heat Gain through Opaque Surface (Walls and Roof):

To predict the effect of sun in the heat transfer from the walls or roofs, a concept of sol-air temperature is used which basically provides an equivalent outside temperature with the solar radiation.

The sol-air temperature is basically defined as:

$$T_{sol-air} = T_{ambient} + \frac{\alpha_s\, \dot{q}_{solar}}{h_o} - \frac{\epsilon\sigma(T_{ambient}^4 - T_{surr}^4)}{h_o}$$

Where

$$\alpha_s = \text{Absorptivity of the Surface}$$
$$\epsilon = \text{Emissivity of the Surface}$$

Absorptivity values of the surface can be seen from below.

TABLE 16–6

The reflectivity ρ_s and absorptivity α_s of common exterior surfaces for solar radiation (from Kreider and Rabl, 1994, Table 6.1)

Surface	ρ_s	α_s
Natural Surfaces		
Fresh snow	0.75	0.25
Soils (clay, loam, etc.)	0.14	0.86
Water	0.07	0.93
Artificial Surfaces		
Bituminous and gravel roof	0.13	0.87
Blacktop, old	0.10	0.90
Dark building surfaces (red brick, dark paints, etc.)	0.27	0.73
Light building surfaces (light brick, light paints, etc.)	0.60	0.40
New concrete	0.35	0.65
Old concrete	0.25	0.75
Crushed rock surface	0.20	0.80
Earth roads	0.04	0.96
Vegetation		
Coniferous forest (winter)	0.07	0.93
Dead leaves	0.30	0.70
Forests in autumn, ripe field crops, plants, green grass	0.26	0.74
Dry grass	0.20	0.80

TABLE 16–7

Sol-air temperatures for July 21 at 40° latitude (from ASHRAE *Handbook of Fundamentals*, Chap. 26, Table 1)

(*a*) *SI units*

Solar time	Air temp., °C	Light-colored surface, $\alpha/h_o = 0.026$ m² · °C/W N	NE	E	SE	S	SW	W	NW	Horiz.
5	24.0	24.1	24.2	24.2	24.1	24.0	24.0	24.0	24.0	20.1
6	24.2	27.2	34.5	35.5	29.8	25.1	25.1	25.1	25.1	22.9
7	24.8	27.3	38.1	41.5	35.2	26.5	26.4	26.4	26.4	28.1
8	25.8	28.1	38.0	43.5	38.9	28.2	28.0	28.0	28.0	33.8
9	27.2	29.9	35.9	43.1	41.2	31.5	29.8	29.8	29.8	39.2
10	28.8	31.7	33.4	40.8	41.8	35.4	31.8	31.7	31.7	43.9
11	30.7	33.7	34.0	37.4	41.1	39.0	34.2	33.7	33.7	47.7
12	32.5	35.6	35.6	35.9	39.1	41.4	39.1	35.9	35.6	50.1
13	33.8	36.8	36.8	36.8	37.3	42.1	44.2	40.5	37.1	50.8
14	34.7	37.6	37.6	37.6	37.7	41.3	47.7	46.7	39.3	49.8
15	35.0	37.7	37.6	37.6	37.6	39.3	49.0	50.9	43.7	47.0
16	34.7	37.0	36.9	36.9	36.9	37.1	47.8	52.4	46.9	42.7
17	33.9	36.4	35.5	35.5	35.5	35.6	44.3	50.6	47.2	37.2
18	32.7	35.7	33.6	33.6	33.6	33.6	38.3	44.0	43.0	31.4
19	31.3	31.4	31.3	31.3	31.3	31.3	31.4	31.5	31.5	27.4
20	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	25.9
Avg.	**29.0**	**30.0**	**32.0**	**33.0**	**32.0**	**31.0**	**32.0**	**33.0**	**32.0**	**32.0**

Solar time	Air temp., °C	Dark-colored surface, $\alpha/h_o = 0.052$ m² · °C/W N	NE	E	SE	S	SW	W	NW	Horiz.
5	24.0	24.2	24.4	24.3	24.1	24.0	24.0	24.0	24.0	20.2
6	24.2	30.2	44.7	46.7	35.4	26.0	26.0	26.0	26.0	25.5
7	24.8	29.7	51.5	58.2	45.6	28.2	28.0	28.0	28.0	35.4
8	25.8	30.5	50.1	61.2	52.1	30.7	30.1	30.1	30.1	45.8
9	27.2	32.5	44.5	58.9	55.1	35.8	32.3	32.3	32.3	55.1
10	28.8	345	38.0	52.8	54.9	42.0	34.7	34.5	34.5	62.8
11	30.7	36.8	37.2	44.0	51.5	47.4	37.7	36.8	36.8	68.5
12	32.5	38.7	38.7	39.3	45.7	50.4	45.7	39.3	38.7	71.6
13	33.8	39.9	39.9	39.9	40.8	50.5	54.6	47.1	40.3	71.6
14	34.7	40.4	40.4	40.4	40.6	47.9	60.8	58.7	43.9	68.7
15	35.0	40.3	40.1	40.1	40.1	43.6	62.9	66.7	52.3	62.9
16	34.7	39.4	39.0	39.0	39.0	39.6	61.0	70.1	59.0	54.7
17	33.9	38.8	37.1	37.1	37.1	37.3	54.7	67.3	60.6	44.5
18	32.7	38.7	34.5	34.5	34.5	34.5	43.9	55.2	53.2	34.0
19	31.3	31.5	31.3	31.3	31.3	31.3	31.4	31.6	31.7	27.5
20	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	25.9
Avg.	**29.0**	**32.0**	**35.0**	**37.0**	**37.0**	**34.0**	**37.0**	**37.0**	**35.0**	**40.0**

Then

$$\dot{Q}_{wall} = UA_s(T_{sol-air} - T_{inside})$$

The solar component of the heat transfer is:

$$\dot{Q} = UA_s\delta T_{solar} = UA_s\frac{\alpha_s\dot{q}_{solar}}{h_o}$$

5.3.2 Solar Heat Gain through Transparent Surface (Glass):

The solar heat gain from the surface of the windows can be calculated as:

$$\dot{Q}_{solar,gain} = SHGC * A_{glazing} * q_{solar,incident}$$

A new coefficient, shading coefficient is used to find the SHGC which is defined as:

$$SC = \frac{Solar\ heat\ gain\ of\ product}{Solar\ heat\ gain\ of\ reference\ glazing} = 1.15 * SHGC$$

TABLE 16–20

Hourly variation of solar radiation incident on various surfaces and the daily totals throughout the year at 40° latitude (from ASHRAE *Handbook of Fundamentals*, Chap. 27, Table 15)

		Solar radiation incident on the surface,* W/m²															
		Solar time															
Date	Direction of surface	5	6	7	8	9	10	11	12 noon	13	14	15	16	17	18	19	Daily total
Jan.	N	0	0	0	20	43	66	68	71	68	66	43	20	0	0	0	446
	NE	0	0	0	63	47	66	68	71	68	59	43	20	0	0	0	489
	E	0	0	0	402	557	448	222	76	68	59	43	20	0	0	0	1863
	SE	0	0	0	483	811	875	803	647	428	185	48	20	0	0	0	4266
	S	0	0	0	271	579	771	884	922	884	771	579	271	0	0	0	5897
	SW	0	0	0	20	48	185	428	647	803	875	811	483	0	0	0	4266
	W	0	0	0	20	43	59	68	76	222	448	557	402	0	0	0	1863
	NW	0	0	0	20	43	59	68	71	68	66	47	63	0	0	0	489
	Horizontal	0	0	0	51	198	348	448	482	448	348	198	51	0	0	0	2568
	Direct	0	0	0	446	753	865	912	926	912	865	753	446	0	0	0	—
Apr.	N	0	41	57	79	97	110	120	122	120	110	97	79	57	41	0	1117
	NE	0	262	508	462	291	134	123	122	120	110	97	77	52	17	0	2347
	E	0	321	728	810	732	552	293	131	120	110	97	77	52	17	0	4006
	SE	0	189	518	682	736	699	582	392	187	116	97	77	52	17	0	4323
	S	0	18	59	149	333	437	528	559	528	437	333	149	59	18	0	3536
	SW	0	17	52	77	97	116	187	392	582	699	736	682	518	189	0	4323
	W	0	17	52	77	97	110	120	392	293	552	732	810	728	321	0	4006
	NW	0	17	52	77	97	110	120	122	123	134	291	462	508	262	0	2347
	Horizontal	0	39	222	447	640	786	880	911	880	786	640	447	222	39	0	6938
	Direct	0	282	651	794	864	901	919	925	919	901	864	794	651	282	0	—
July	N	3	133	109	103	117	126	134	138	134	126	117	103	109	133	3	1621
	NE	8	454	590	540	383	203	144	138	134	126	114	95	71	39	0	3068
	E	7	498	739	782	701	531	294	149	134	126	114	95	71	39	0	4313
	SE	2	248	460	580	617	576	460	291	155	131	114	95	71	39	0	3849
	S	0	39	76	108	190	292	369	395	369	292	190	108	76	39	0	2552
	SW	0	39	71	95	114	131	155	291	460	576	617	580	460	248	2	3849
	W	0	39	71	95	114	126	134	149	294	531	701	782	739	498	7	4313
	NW	0	39	71	95	114	126	134	138	144	203	383	540	590	454	8	3068
	Horizontal	1	115	320	528	702	838	922	949	922	838	702	528	320	115	1	3902
	Direct	7	434	656	762	818	850	866	871	866	850	818	762	656	434	7	—
Oct.	N	0	0	7	40	62	77	87	90	87	77	62	40	7	0	0	453
	NE	0	0	74	178	84	80	87	90	87	87	62	40	7	0	0	869
	E	0	0	163	626	652	505	256	97	87	87	62	40	7	0	0	2578
	SE	0	0	152	680	853	864	770	599	364	137	66	40	7	0	0	4543
	S	0	0	44	321	547	711	813	847	813	711	547	321	44	0	0	5731
	SW	0	0	7	40	66	137	364	599	770	864	853	680	152	0	0	4543
	W	0	0	7	40	62	87	87	97	256	505	652	626	163	0	0	2578
	NW	0	0	7	40	62	87	87	90	87	80	84	178	74	0	0	869
	Horizontal	0	0	14	156	351	509	608	640	608	509	351	156	14	0	0	3917
	Direct	0	0	152	643	811	884	917	927	917	884	811	643	152	0	0	—

*Multiply by 0.3171 to convert to Btu/h · ft².

Figure 5 Variation of Solar Radiation Intensity

TABLE 16–21

Shading coefficient SC and solar transmissivity τ_{solar} for some common glass types for summer design conditions (from ASHRAE *Handbook of Fundamentals*, Chap. 27, Table 11)

Type of glazing	Nominal thickness mm	Nominal thickness in	τ_{solar}	SC*
(*a*) Single Glazing				
Clear	3	1/8	0.86	1.0
	6	1/4	0.78	0.95
	10	3/8	0.72	0.92
	13	1/2	0.67	0.88
Heat absorbing	3	1/8	0.64	0.85
	6	1/4	0.46	0.73
	10	3/8	0.33	0.64
	13	1/2	0.24	0.58
(*b*) Double Glazing				
Clear in, clear out	3[a]	1/8	0.71[b]	0.88
	6	1/4	0.61	0.82
Clear in, heat absorbing out[c]	6	1/4	0.36	0.58

*Multiply by 0.87 to obtain SHGC.

[a]The thickness of each pane of glass.

[b]Combined transmittance for assembled unit.

[c]Refers to gray-, bronze-, and green-tinted heat-absorbing float glass.

Figure 6 Shading Coefficients

5.4 Modelling and Estimate Value of A (IV)

5.4.1 Scenario:

During normal conditions, there is lighting turned on inside rooms which also produces heat, so they have to modelled.
The heat given off by a light is:

$$Q = 3.41 * W * F_{UT} * F_{SA} * CLF$$

Where
$W = Watts\ input$
$F_{UT} = Lightning\ use\ factor$
$F_{SA} = Special\ Ballast\ Allowance\ Factor$
$CLF = Cooling\ Load\ Factor$

1. Generally, special blast allowance is used for fluorescent fixtures (tubes and lamps) and it accounts for ballast losses. **It's value is generally taken as 1.25**. It is a fraction of total heat that is expected to enter the conditioned space due to ballast and it subject to time lag effect.
2. U[1]se factor is the ratio of actual wattage in use to installed wattage and it is **taken as 1 for domestic** purposes
3. The **value of 0.7** has been used for the CLF

5.5 Modelling and Estimate Value of A (VIII)

5.5.1 Scenario:

The cooling load from motors has been explained in **Modelling and Estimate Value of A (IV)** and in this section, the approximate motor powers have been listed for them to be used in the modelling.

Table 6 Ceiling Fans

Brand Name	Fan Type	Rated Power
Royal Fans	Ceiling Fan 36'', 48'' and 56''	55, 65 and 75W
GFC	Ceiling Fan	80W
Pak Fans	Ceiling Fan 36'', 48'' and 56''	55, 62, and 70W

5.6 Modelling and Estimate Value of B (II):

5.6.1 Latent Heat Transfer from Human Body:

The latent heat transfer from humans has basically three components, one is the moisture on the skin, the second is the body loses both sensible heat by convection and latent heat by evaporation from the lungs.

5.6.2 Latent Heat Transfer from the Skin

Latent heat loss from the skin can be calculated as:

$$\dot{Q} = \dot{m}_{vapor} h_{fg}$$

Where

$\dot{m}_{vapor} = Rate\ of\ evaporation\ from\ the\ body, \frac{kg}{s}$

[1] At maximum intensity, during a workout on a hot day the human body can lose as much as 0.3 g/s of water from the body which corresponds to heat loss rate of about 730 W.

$$h_{fg} = Latent\ heat\ of\ vaporization\ of\ Water = 2430\frac{kJ}{kg}\ @\ 30°C$$

5.6.3 Sensible and Latent Heat Transfer from the Lungs:

The sensible heat transfer has only convection component and is related as:

$$\dot{Q}_{sensible,conv_{lungs}} = \dot{m}_{air,lungs}c_{p,air}(T_{exhale} - T_{ambient})$$

Where,

$$\dot{m}_{air,lungs} rate\ of\ air\ to\ the\ lungs$$

The latent heat transfer is related as:

$$\dot{Q}_{latent,lungs} = \dot{m}_{vapor,lungs}h_{fg} = m_{air,\dot{l}ungs}(\omega_{exhale} - \omega_{ambient})h_{fg}$$

Where

$$T_{exhale} = temperature\ of\ the\ exhaled\ air$$
$$\omega = humidity\ ratio$$

@ 25°C, the value of heat capacity of air $c_p = 1.006\frac{kJ}{kg.K}$

The combination of latent and sensible heat loss from the lungs can be approximated as:

$$\dot{Q}_{sensible+Latent} = 0.0014\ \dot{Q}_{met}\ (34 - T_{ambient}) + 0.0173\dot{Q}_{met}(5.87 - P_{v,ambient})$$

Where,

$P_{v,ambient}$ is the vapor pressure of ambient air in kPa

$\dot{Q}_{met} = Human\ Metabolic\ Rate$

Chapter 6. Model Parameters

The parameters of the Simulink Model are referenced from the different MATLAB Scripts. Default values are already written but in case, a user wants to change the scenarios such as changing the room size or change the solar load according to the specific region, they would have to change the parameters values in the scripts.

The scripts are named according to the categories explained in **Chapter 2.1: Methodology.** Hence each script will contain parameters related to the category of cooling loads. Furthermore, the scripts itself contains comments to provide the information about their units and purpose. Each variable name is pneumonic for the user to quickly identify the relevant parameter.

6.1 Parameters of Category A (I)

6.1.1 Properties and Parameters of External Walls

```
%Exterior Convection Parameters
l_wall_exterior=10 ;%m
w_wall_exterior=10; %m
h_room= 2; %m
area_wall_exterior=l_wall_exterior*w_wall_exterior; %m^2
hc_wall_exterior= 34; %W/m^2.K
%Interior Convection Parameters
hc_wall_interior= 24; %W/m^2.K
%Exterior Conduction Parameters
thicnkess_wall_exterior=0.2 ;%m
k_wall=0.038 ;%W/m.K
%Interior Conduction Parameters
% Same as Exterior
%Thermal Properties of Exterior Walls
rho_wall=1920; %kg/m^3
mass_wall_exterior=rho_wall*area_wall_exterior*thicnkess_wall_exterior; %kg
cp_wall_exterior= 835; %j/K.kg
T_init_wall=  25; % degC
```

6.1.2 Properties and Parameters of Windows

```
%Exterior Convection Parameters
l_window= 0.3;%m
w_window= 0.2;%m
area_window=l_window*w_window; %m^2
hc_window_exterior=32; %W/m^2.K
%Interior Convection Parameters
hc_window_interior=25; %W/m^2.K
%Exterior Conduction Parameters
thicnkess_window= 0.01; %m
k_window= 0.78; %W/m.K
%Interior Conduction Parameters
% Same as Exterior
%Thermal Properties of Exterior Walls
rho_window= 2700; %kg/m^3
mass_window=rho_window*area_window*thicnkess_window; %kg
cp_window= 840; %j/K.kg
T_init_window= 25; % degC
```

6.1.3 Properties and Parameters of Furniture

```
%Interior Convection Parameters
l_furniture=4.5; %m
w_furniture=2.5 ;%m
area_furniture=l_furniture*w_furniture; %m^2
hc_furniture_interior=18; %W/m^2.K
%Thermal Properties of Exterior Walls
mass_furniture=400;%kg
cp_furniture=2000;%j/K.kg
T_init_furniture= 25; % degC
```

6.1.4 Properties and Parameters of Roof

```
%Exterior Convection Parameters
l_roof= 5;%m
w_roof= 3;%m
pitch_roof= 40;%deg
area_roof=l_roof*w_roof; %m^2
hc_roof_exterior= 38; %W/m^2.K
%Interior Convection Parameters
hc_roof_interior= 12 ;%W/m^2.K
%Exterior Conduction Parameters
thicnkess_roof= 0.2; %m
k_roof= 0.038; %W/m.K
%Interior Conduction Parameters
% Same as Exterior
%Thermal Properties of Exterior Walls
rho_roof= 32; %kg/m^3
mass_roof=rho_roof*area_roof*thicnkess_roof; %kg
cp_roof= 835; %j/K.kg
T_init_roof=25 ;% degC
```

6.1.5 Properties and Parameters of Environment

```
T_env=35 ;%degC
T_house_init=27; %degC
T_Set=18; %degC
```

6.2 Parameters of Category A (II)

6.2.1 Solar Data:

```
[483,811,875,803,647,428,185,48,20,0]; % Solar Radiation of South-East Wall from 8am to 5pm
[402,557,448,222,76,68,59,43,20,0]; % Solar Radiation of East Wall from 8am to 5pm
[271,579,771,884,922,884,771,579,271,0]; % Solar Radiation of North Wall from 8am to 5pm
absorptivity_surface=0.65;
```

6.3 Parameters of Category A (II)

```
%Properties and Parameters Related to Lights
no_lights=4; %no of lights
wattage_per_light= 12; %Watts
F_UT=1;
CLF=0.7;
F_SA=1.25;
Q_lights=3.41*no_lights*F_UT*F_SA*CLF*wattage_per_light; %W
```

6.4 Parameters of Category A (V)

```
%Properties and Parameters Related to Occupant
no_occupants=2;
area_clothing= 1.8; %m^2
T_skin= 33; %degC
T_surr=25; %degC
%T_operative= (T_env+T_surr)/2 %degC
R_clothing=0.0775; %m^2.degC/W
velocity_air=0.7 ;%m/s
h_conv=8.3*velocity_air^0.6; %W/m^2.degC
h_radiation= 4.7; %W/m^2.degC
h_combined= h_conv+h_radiation;
Q_occupant= area_clothing*(T_skin-T_surr)/(R_clothing+1/h_combined); %W
```

6.5 Parameters of Category A (VI)

```
rho_outdoor= 1.2 ;  %kg/m^3
cp_air = 1; %kj/kg/K
%V_dot=  %m^3/s
T_indoor=out.T_room.signals.values;
ACH= 0.55 %Air Changes per Hour
V_room = l_wall_exterior*w_wall_exterior*h_room; %m^3
Q_infiltration_sensible= rho_outdoor*cp_air*ACH*V_room*(T_env-T_indoor);
Q_infiltration_average=sum(Q_infiltration_sensible(:,:,1:20))/20;
```

6.6 Parameters of Category A (VIII)

```
%Properties and Parameters Related to Ceiling Fan
no_motors=1;
Average_Power_Rating_Motor= 75; %W
Efficiency_Motor= 0.6;
Load_Factor= 0.55;
Q_motor=no_motors*Average_Power_Rating_Motor/Efficiency_Motor*Load_Fac
tor;
```

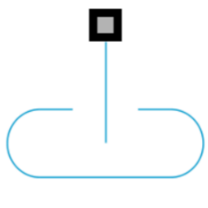
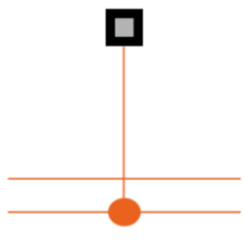
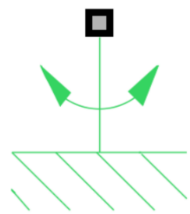
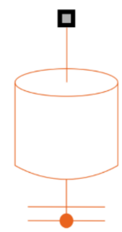
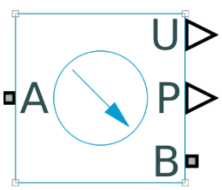
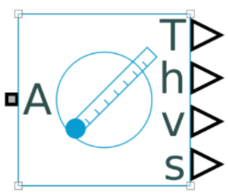
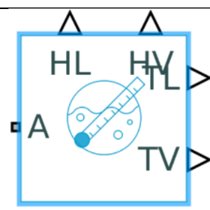
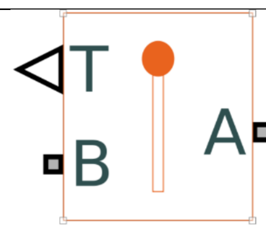
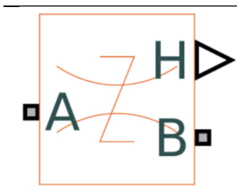
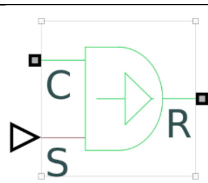
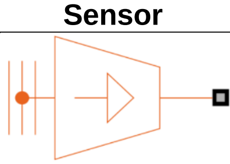
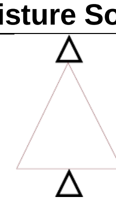
6.7 Parameters of Category B (II)

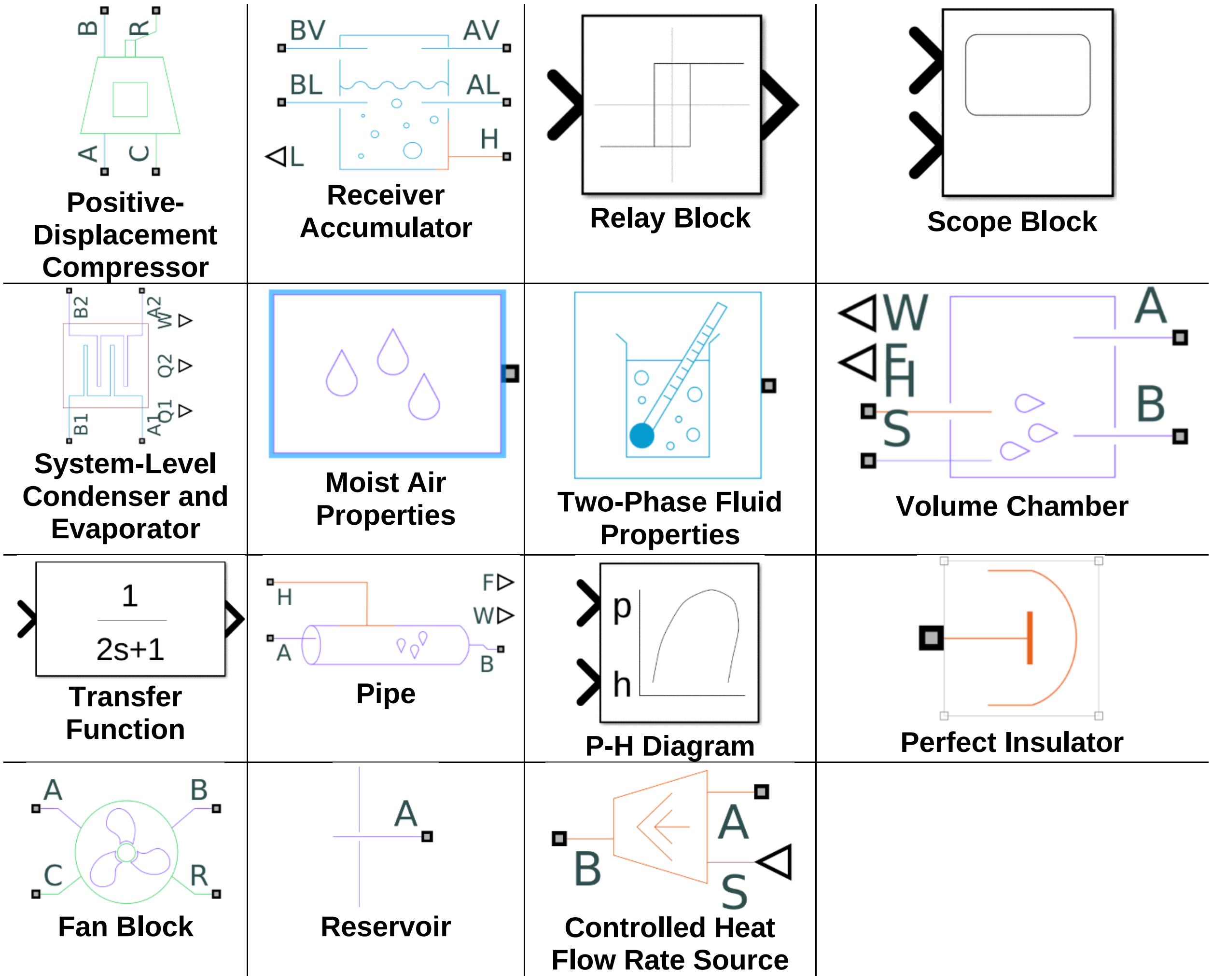
6.7.1 Parameters Related to Refrigeration Unit

```
%Evaporator Parameters
evp_diam_A1=6.35*10^-3; %m;
evp_diam_A2=6.35*10^-3; %m;;
evp_diam_B1=7*10^-3; %m;
evp_diam_B2=7*10^-3; %m;;
%Condenser Parameters
cond_diam_A1=4.76*10^-3; %m;
cond_diam_A2=4.76*10^-3; %m;;
cond_diam_B1=6.35*10^-3; %m;
cond_diam_B2=6.35*10^-3; %m;;
%Thermal Expansion Valve Parameters
optimal_rating=5250; %Watts
maximum_rating =5500; %Watts
```

Chapter 7. Model Blocks

All the blocks shown below **are hyperlinked** to provide explanation about what each block does and how it is used.

 **Absolute Reference**	 **Thermal Reference**	 **Rotational Reference**	 **Thermal Mass**
 **Pressure and Internal Energy Sensor**	 **Thermodynamic Properties Sensor**	 **Saturation Properties Sensor**	 **Temperature Sensor**
 **Heat Flow Rate Sensor**	 **Ideal Angular Velocity Source**	 **Heat Flow Rate Source**	 **Moisture Source**
 **Temperature Source**	 **Flow Resistance**	 **From Block**	 **Gain Block**



Chapter 8. Model Navigation

Figure 7 shows the very top level of the model. From this figure we can see that different blocks are used to achieve different results and mechanisms. More information about what each block does, can be referenced from **Chapter 7: Model Blocks.**

8.1 Top-Level Model

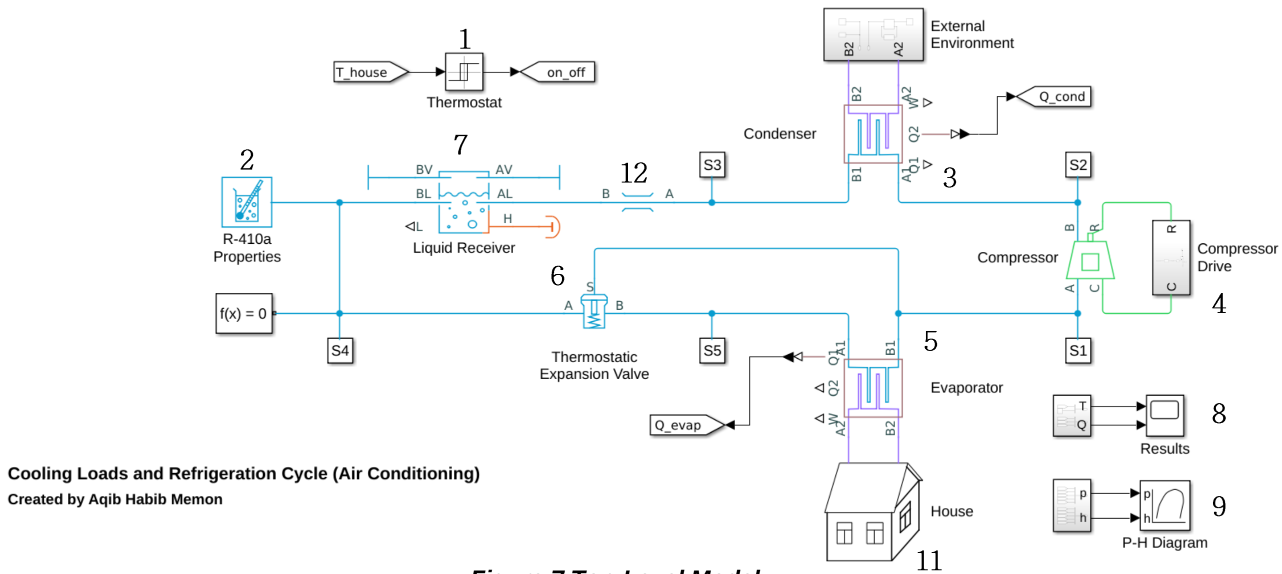


Figure 7 Top-Level Model

Table 7 Top-Level Model Components

Component Number	Component Purpose/Definition
1	The thermostat provides a set point for the refrigeration system and the model will try to maintain this temperature.
2	This block models the properties of the refrigerants being used. Custom properties can also be used if the use has data
3	Condenser is modelled using this block and basically it removes the heat of the refrigerant that it has acquired from the evaporator and compression
4	The compressor and compressor drive contains control, and the compressor will shut down once a set temperature is reached.
5	The evaporator is modelled using this block and the refrigerant in the evaporator absorbs the heat from the room making the room air cooler while the refrigerant gets hotter.
6	TEV is used to control the performance of the evaporator such as the cooling capacity which cannot be directly controlled through the evaporator block.
7	Accumulator is modelled using this block which models the phase change and vapor and liquid mixture during throttling.
8	The results of the model such as cooling load, temperature of room and the power of the evaporator is shown by this scope block
9	The operating points of refrigeration cycle can

	be seen using this block
10	This sub-system block models the external environment such as mass flow rate and moisture in the external air.
11	This sub-system block contains the cooling loads, thermal resistance network and moisture gain from the different occupants and machines.
12	This flow resistance basically models the throttling valve and pressure drop in the model.

The parameters that are mentioned in Chapter 6: Model Parameters are used by the different blocks in the Top and sub-level models.

8.2 Sub-Level Models

8.2.1 House

This sub-system contains the cooling loads that are coming from different sources such solar, occupants, lights, ceiling fans and appliances The environment temperature and room temperature is also being monitored here.

There are also blocks which models the moisture gain from occupants and appliances and this air goes to the evaporator in the top-level model.

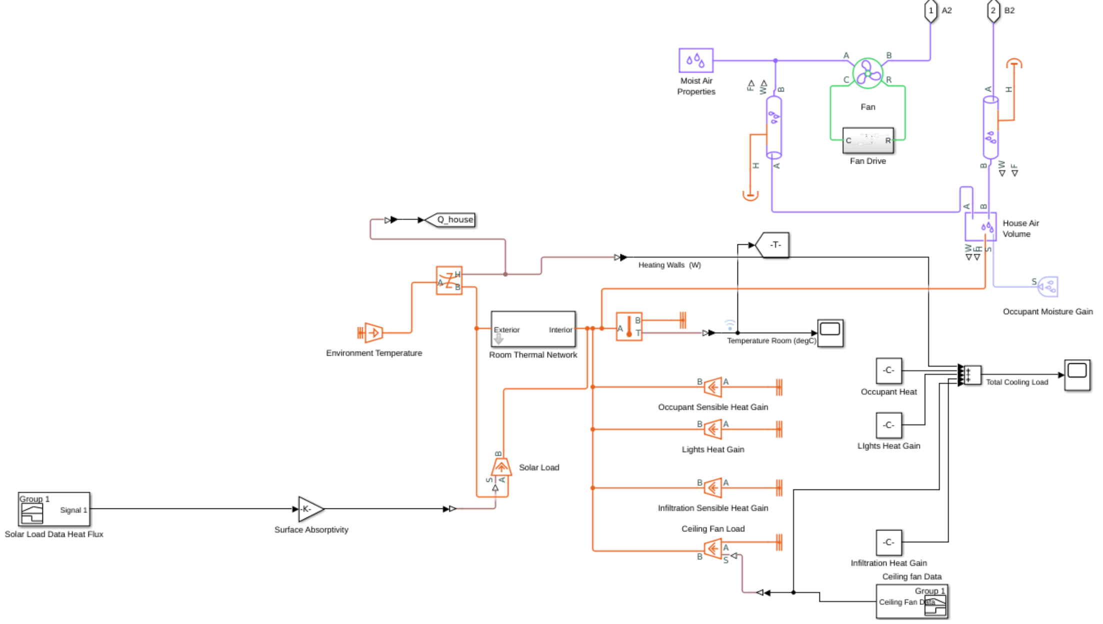


Figure 8 Sub-Level Model of House

Figure 9 shows the room thermal network, that contains the parameters of and models of roof, walls, furniture, and any windows. The parameters can be seen in **Figure 10.**

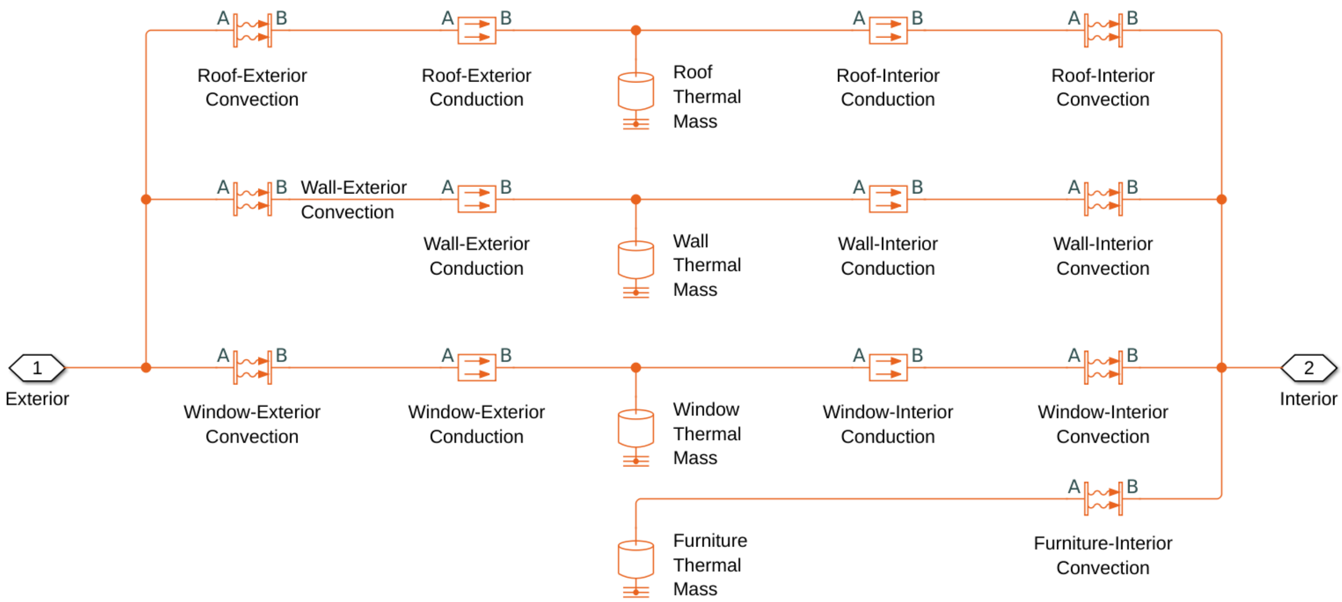


Figure 9 Room Thermal Network

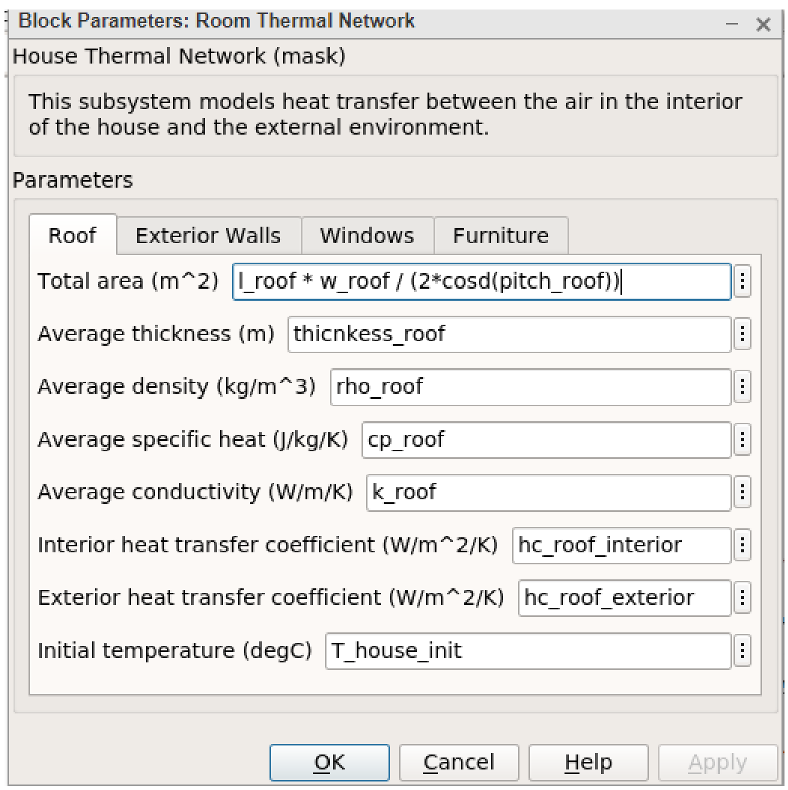


Figure 10 Input Parameters of Thermal Network

The behavior of the loads can be updated from this section of the model as different behavior is recorded for different scenarios. For example, over the day the solar loads vary and becomes maximum in the noon. To model such behavior, we can define custom signals such as shown in **Figure 11.**

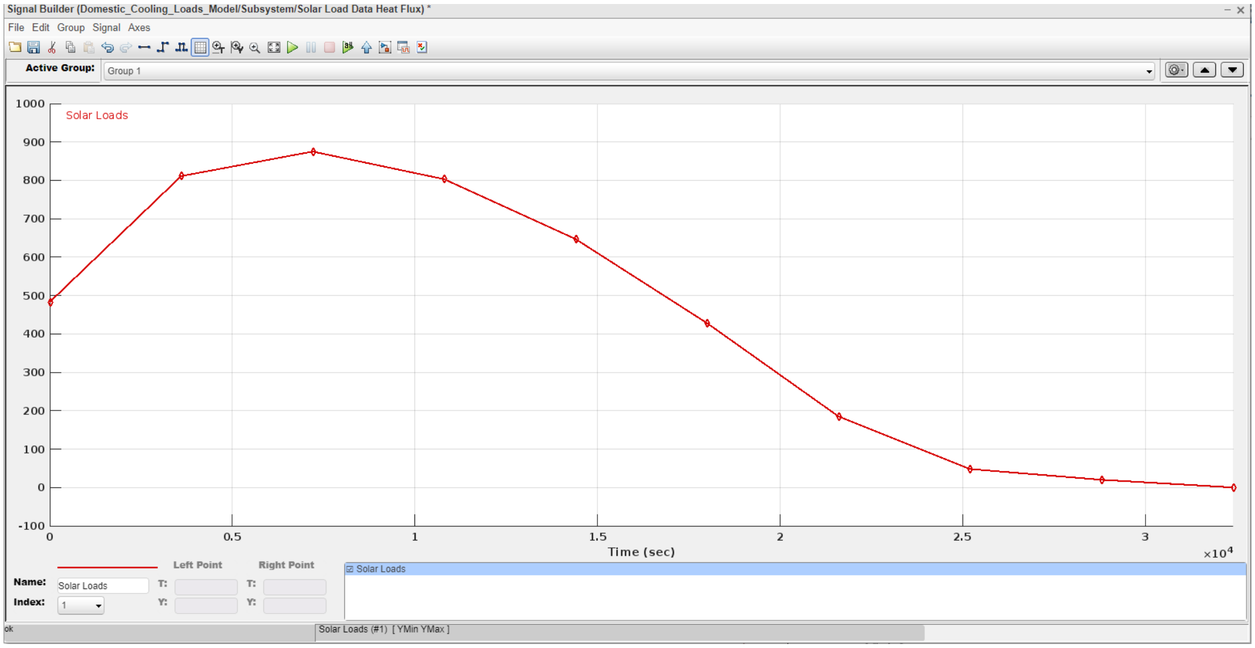


Figure 11 Behavior of Solar Irradiation

Simple scenarios can also be used such as for the ceiling fan being turned on and off at different times for different periods of time as shown in **Figure 12.**

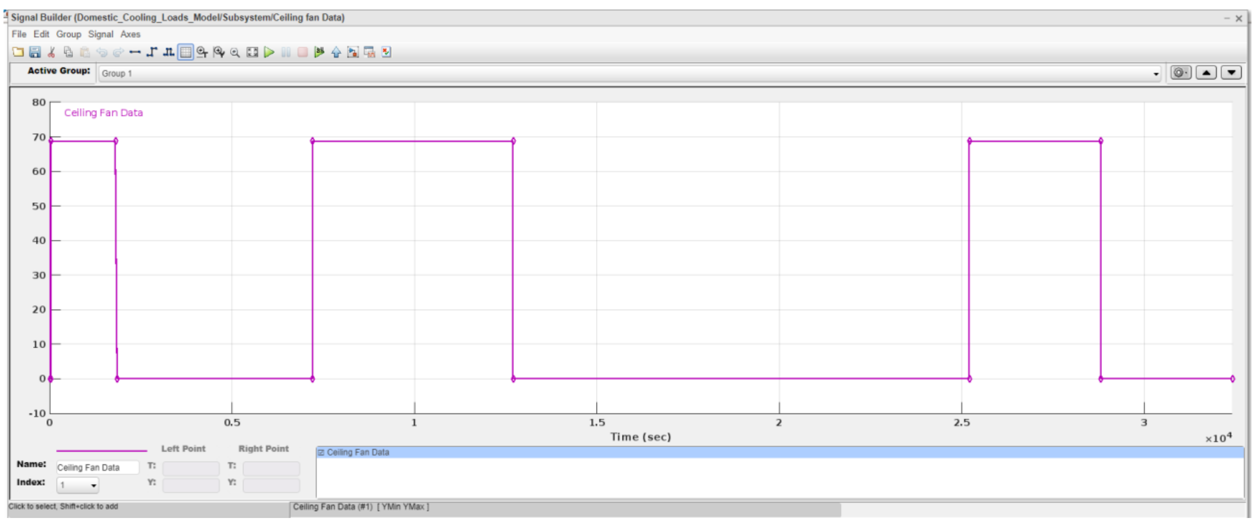


Figure 12 Behavior of Ceiling Fan

8.2.2 External Environment

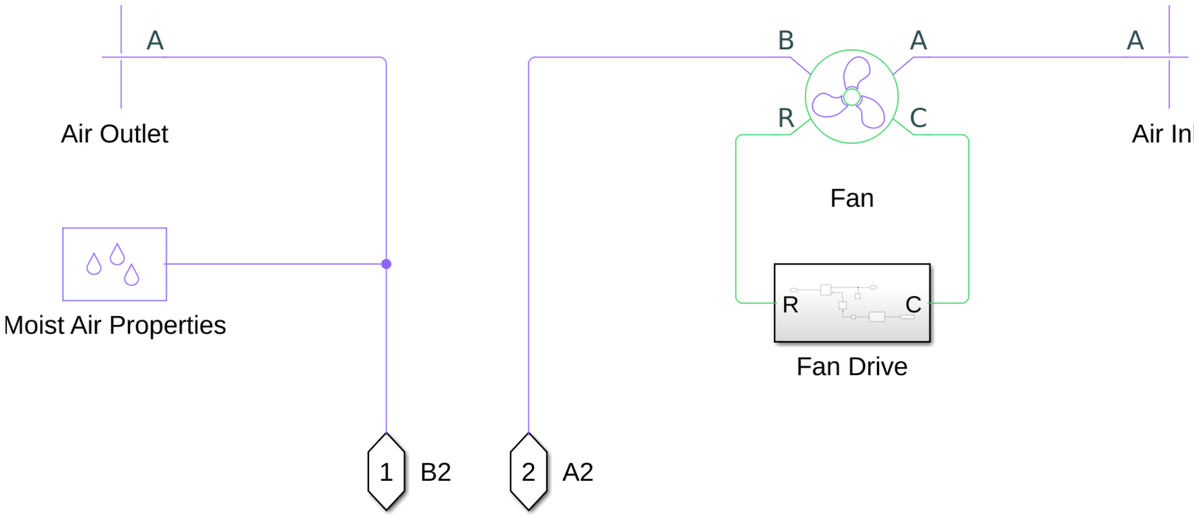


Figure 13 Sub-Level Model of External Environment

The air from the external environment is modelled by using this subsystem as shown in **Figure 13**. The moisture and mass flow rate are controlled by the respective blocks.

8.2.3 Compressor Drive

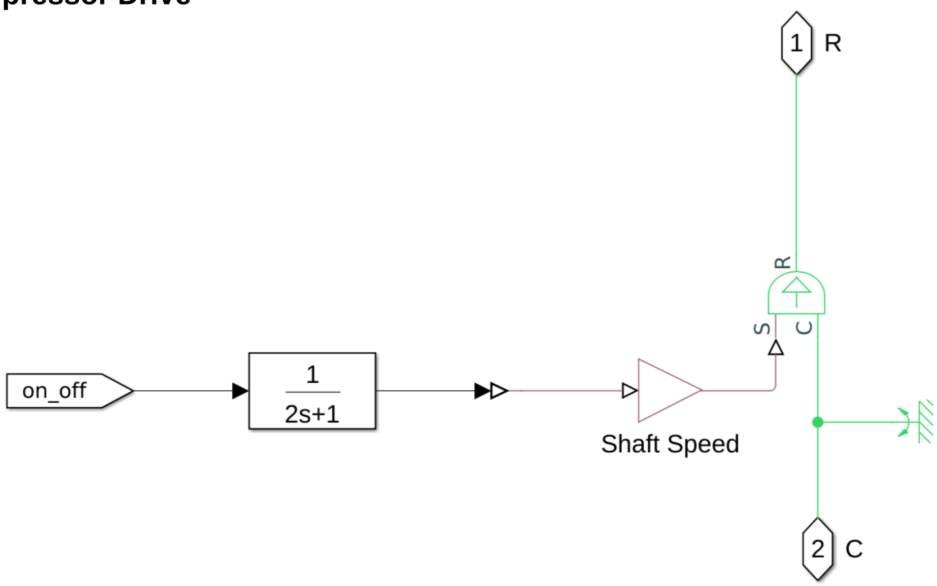


Figure 14 Sub-Level Model of Compressor Drive

The compressor motor and drive are modelled by these blocks which uses output from thermostat and transfer function block to drive the compressor as shown in **Figure 14.**

Chapter 9. Model Results

The main result obtained from the model is the change of cooling load over time.
This can be achieved when all the cooling loads and their behavior are modelled and as well as the other input parameters are provided.