

VOLUME FOUR

Heating, Ventilation and Air Conditioning Systems

1. Introduction

In domestic, institutional and industrial processes, energy is partly used to regulate operating conditions such as temperature, humidity and dust levels. For example: conditions in offices and meeting halls require appropriate temperature and humidity for human comfort; data centres call for low temperatures and dust levels; grain storage facilities require low humidity and dust levels while machine parts like rollers, gear drives and dies require cooling to avoid thermal expansion. During energy audits, the auditor should familiarize themselves with the specific system condition requirements and analyse the related energy demand needs for optimal usage.

To achieve the system condition requirements, the facility should have necessary equipment. The type, number and complexity of air-conditioning system will depend on process required to achieve desired system conditions. A typical air conditioning system will have a heating and a cooling system. The heating system can encompass steam or water boilers, electric resistance heaters and heat pumps, while cooling systems can have cooling towers or gas compression cycles.

The gas compression cycle is the most common component in the heating, ventilation and air-conditioning (HVAC) systems. In this cycle, a low boiling point fluid, referred to as a refrigerant, is used to extract heat from a lower-temperature region and to higher-temperature region. To release the heat to a higher temperature region, the refrigerant pressure should be raised several times above atmospheric temperature. Figure 1 shows a gas compression cycle highlighting heat flow and its respective T-S diagram.

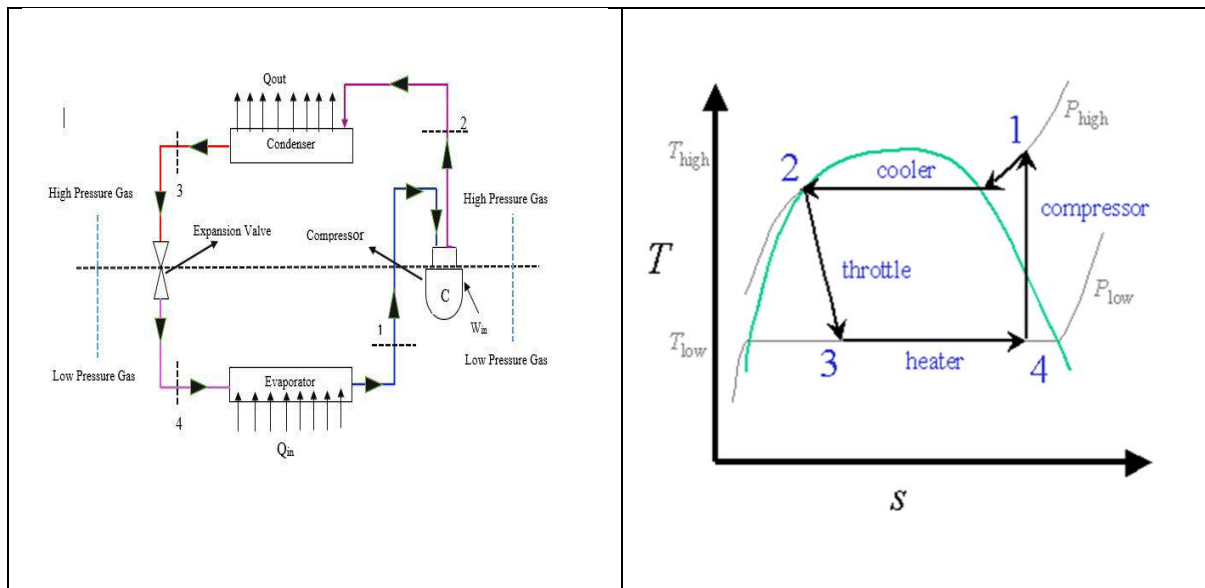


Figure 1: Gas Compression Cycle and T-S diagram

A compressor is used to raise refrigerant pressure above atmospheric pressure. The compressor is the prime mover in the refrigeration cycle hence the only energy consuming unit. This is the energy responsible for moving heat from low temperature region to high temperature region (recall The Second Law of Thermodynamics). The evaporator and the condenser consist of the cooled space and heat sink, respectively, and associated accessories. Throttle (Expansion) valve controls flow and reduces pressure to facilitate phase change. The process explained in Figure 1 is rudimentary. The actual HVAC system is composed of several components, as discussed in subsequent sections of this volume.

This volume focuses on auditing of the HVAC systems. It provides a systematic approach for analysing the energy consumption in the HVAC systems. The volume discusses components of HVAC systems, focusing on various applications. It further guides on the process auditing steps for the system. Lastly, it delves into possible energy conservation measures that an auditor can propose when auditing the system.

2. Components of a heating ventilation and air conditioning system (HVAC)

To effectively audit the HVAC systems, one should go beyond understanding the vapour compression cycle and appraise themselves with the components of the system. Figure 2 illustrates the components of the HVAC system.

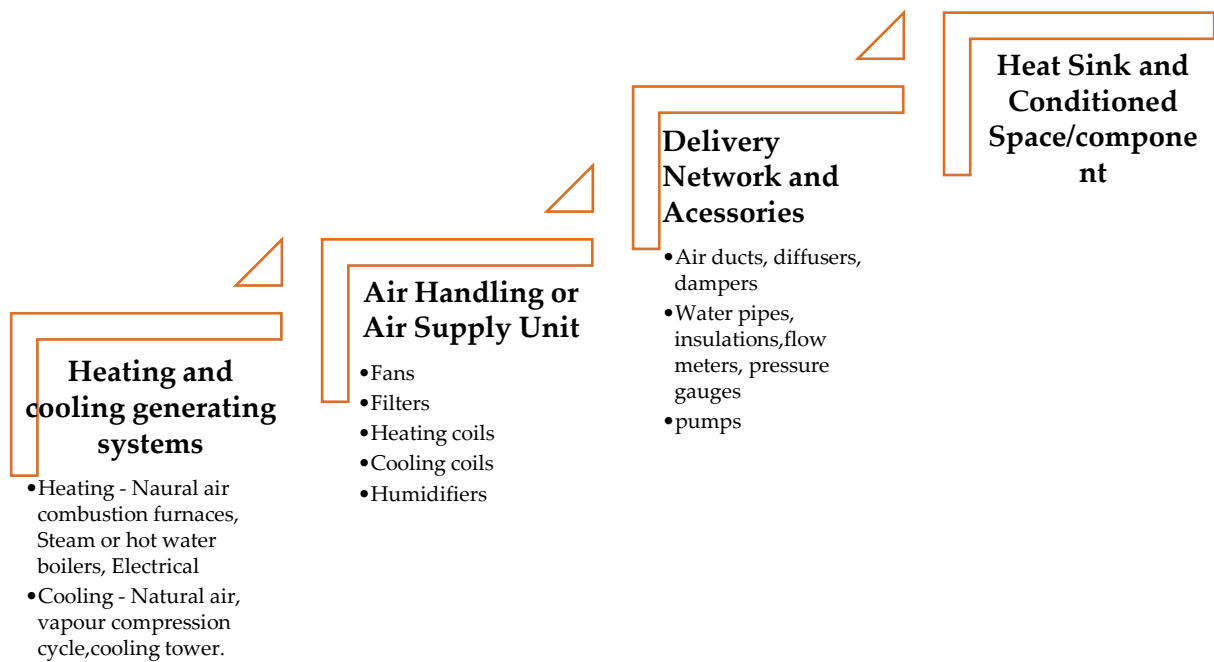


Figure 2: Components of the HVAC system.

The components presented in figure 2 play an integral role in heating or cooling spaces and systems. Some of the components use energy whereas others are accessories to the process.

Heating and cooling generating systems

This part of HVAC system either adds or extracts heat from the working fluid, as case may be for heating or cooling (conditioned working fluid). In either case, energy is utilized. The source of energy depends on the type and configuration of the system.

Air Handling or Air Supply Unit

In some space conditioning systems, there is an emphasis on controlling more than just the air temperature. Parameters such as humidity, particulate matter and odour may be of importance for human comfort. Air handling units assist in achieving these desired parameters.

Delivery Network and Accessories

Once the working fluid has been conditioned using the heating or cooling generator, it has to be circulated between the conditioned space and the heat sink using the delivery network and the accessories.

Conditioned Space
or component, and
Heat Sink

The main aim of HVAC system is to achieve the desired operational system parameters within specified boundaries. These boundaries define the conditioned space or components.

3. Process Auditing Steps for HVAC Systems.

The energy auditing of HVAC systems has three fundamental steps as illustrated in figure 3

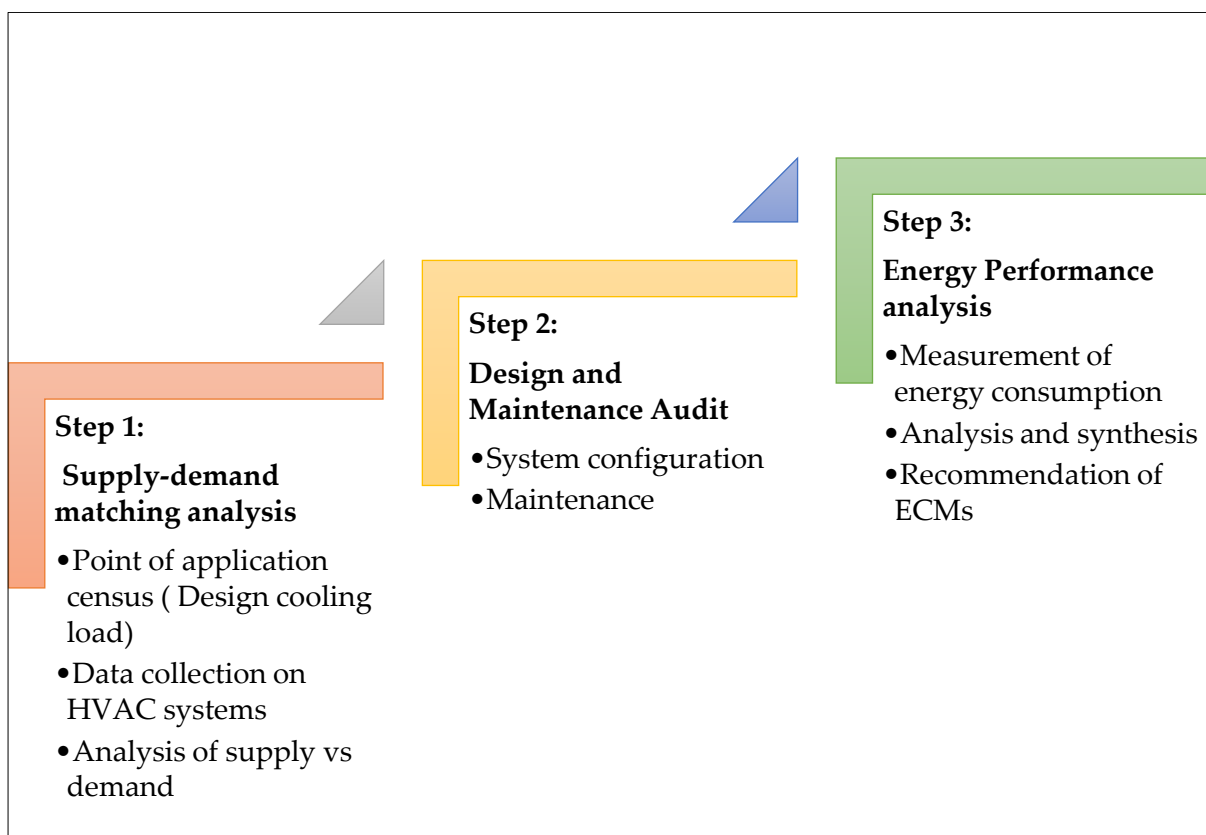


Figure 3:Steps in auditing pumping systems

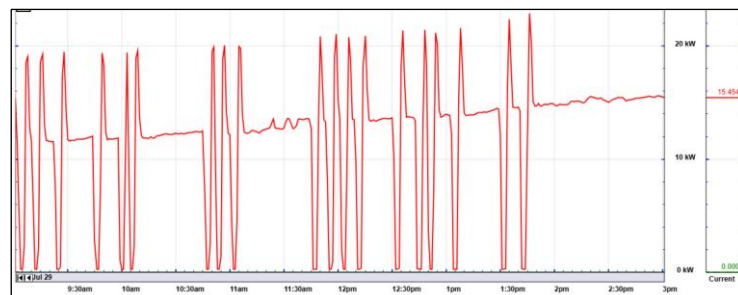
The processes illustrated in Figure 3 are sequential, with the results from the preceding step informing the analysis of the succeeding step.

Step 1: Supply-demand matching analysis

For efficient operation of HVAC systems, the capacity of the heating and cooling generator should match the cooling or heating load requirements. It is instrumental to note that there is no one standardized method of estimating demand in HVAC systems due to their varied system configurations and applications. For example,

determining cooling demand requirements for a cold room is different from that of cooling moving parts of a machine or a conference hall. Specific approaches of estimating demand will be discussed in the example section. That notwithstanding, situations where the capacity is either oversized or undersized will always lead to inefficient operations due to:

Poor loading factor	The efficiency of the generator has been empirically established to increase with the loading factor up to a certain limit. Best practice requires the loading factor should be above 75%.
Frequent sudden starts and stops	An oversized generator will be subjected to frequent starts and stops as a result of instantaneously meeting demand requirements. Such operating conditions lead to increased cases of inrush currents (see the illustration), which are five to seven times higher running currents, leading to overheating.



Step 2: Design, Operation and Maintenance Audit

The performance of HVAC systems depends on its design, operation and maintenance. During an energy audit, the auditor should assess whether the system has been properly sized and if the operating conditions have been set optimally. For sizing, the system components should have the correct power ratings, which should correspond to the desired component output. Let us consider a fan in a ducted HVAC system. The auditor should check whether rating of the fan motor is in tandem with the air flow rate and pressure requirement.

The auditor should take into consideration the operating parameters and conditions. Understanding the design and operating principles of the HVAC system is therefore central to energy auditing.

Figure 4 can be used to guide the auditor on procedural steps of auditing the system design and maintenance.

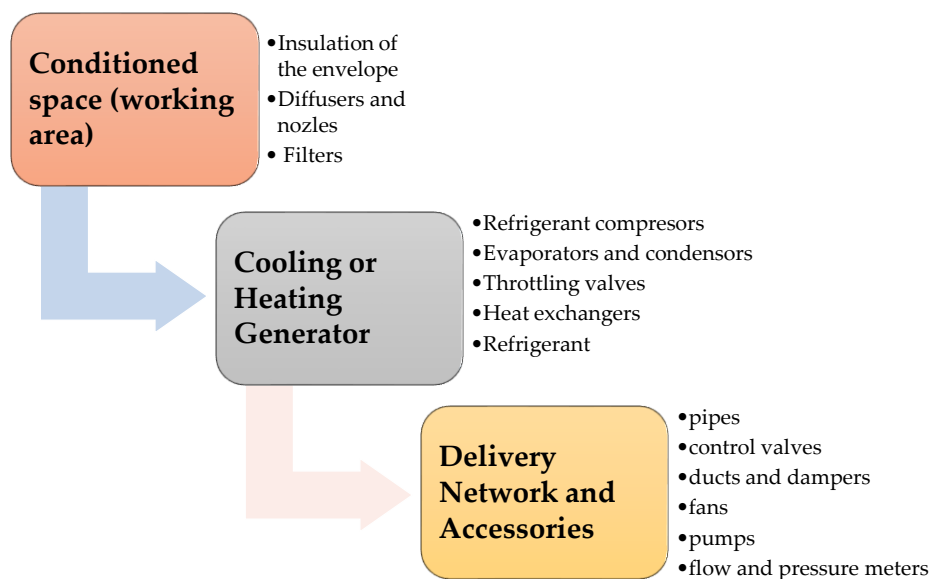


Figure 4: Steps of auditing the system design and maintenance

Conditioned Space (working area)

The major operating parameters of conditioned space in HVAC system are: set temperature, relative humidity, air speed, particulate matter and odour. The parameters are informed by standards governing the operation under discussion. The auditor should therefore refer to the standards and design manual. For example, in a food handling facility, the hazard analysis critical control point (HACCP) food safety management system requirements could be used in setting operation parameters of a cold room. The recommended temperature here for hazardous food should be kept at 5°C. Likewise, the air flow in a conditioned space should be set to a comfortable level. ASHRAE set standards is 0.2m/s to 2.0m/s. Similarly, the relative humidity levels are guided by the ASHRAE standards.

Once the auditor establishes the prevailing operating conditions and compares them to the standard requirements, they can recommend changes. Observed deviations could be attributed to maintenance problems, poor design or operation settings. Recommended changes from an auditor should include changing the temperature, humidity and air speed set points, improving insulation and optimal loading. These changes can either improve the quality of processes or translate to energy conservation measures.

Cooling or Heating Generator

In a vapour compression cycle, the auditor should focus on temperature, pressure and flow rate of the refrigerant in both the high- and low-pressure zones. The auditor should check the minimum operating pressure and temperature of the refrigerant in the evaporator. Likewise, the auditor should check the maximum operating pressure and temperature after the compressor. The flow rate of the refrigerant affects the efficiency of the system. Higher flow rate than

recommended can lead to overcooling and vice versa. The auditor should therefore check if the flow rate is within the manufacturer's recommendation. On maintenance the auditor should check for refrigerant leaks, cleanliness of the condenser, evaporator and the compressor vibrations. The auditor should also check the synchronization of the system to reduce losses especially due to idle running. For example, in a cold room, once the compressor shuts down, the condenser fan should stop running after 5 minutes. There are some poor operational cases where the compressor could be off yet the condenser fan continues running for longer than necessary.

The operations and maintenance of the delivery system have been handled in the pumping and fan systems. The next part of this volume discusses practical examples of auditing various HVAC systems.

3.1.Auditing Vapour Compression Cycle

The energy efficiency (performance) of a vapour compression cycle is measured using the coefficient of performance (COP) or the energy efficiency ratio (EER):

$$COP_{cooling} = \frac{Q_{in}}{W_{in}} \quad (1)$$

Where

Q_{in} is heat drawn from low temperature area to the refrigeration cycle

W_{in} is power input to the refrigeration cycle

For the case of a heat pump, the COP is determined by equation 2.

$$COP_{heating} = \frac{Q_{out}}{W_{in}} \quad (2)$$

Q_{out} is Heat released from the condenser

W_{in} is power input to the refrigeration cycle

For efficient operation, the calculated COP should be as close as possible to the manufacturer's specification. Currently in the market, COP ranges from 3.5 to 6.0 (for cooling) and from 3.5 to 8.0 (for heating). The values of Q and W are determined using field measurements. Consider figure 2 as a typical vapour compression cycle under discussion.

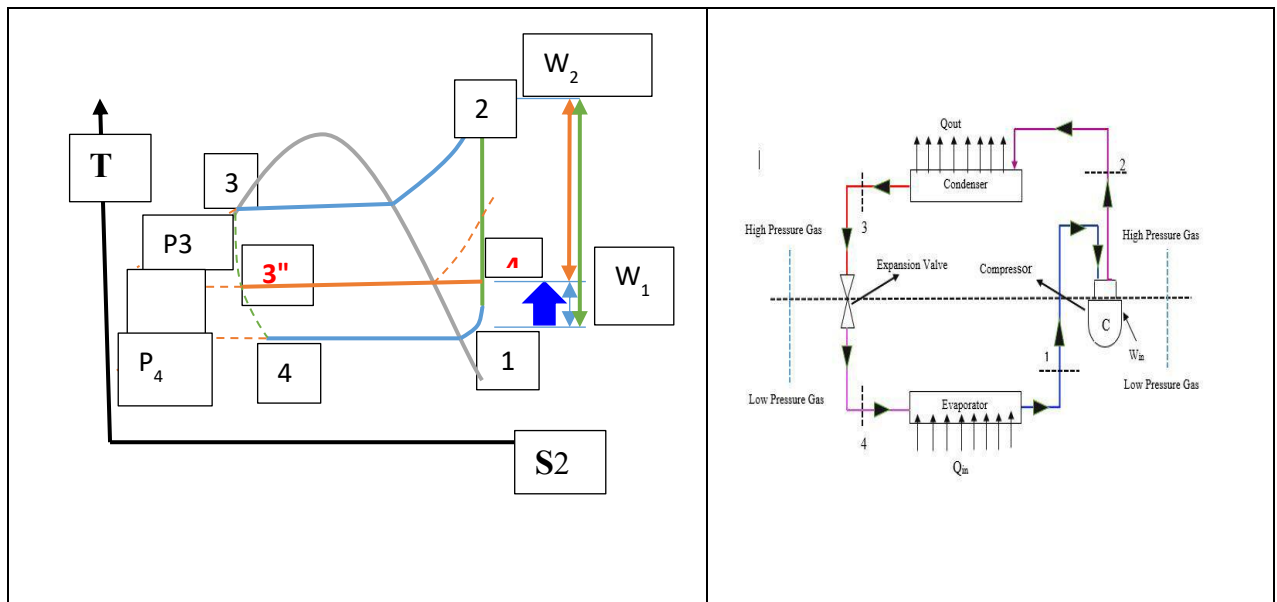


Figure 2: T-S diagram demonstrating power reduction by increasing evaporator operating temperature

In order to establish the COP in an energy audit, measurements of temperature, pressure, refrigerant flow and power consumption should be measured. Temperatures and pressure should be measured at:

- i. Evaporators
- ii. Entrance to the condensers
- iii. Exit from the condensers to the expansion valve

Note:

- i. Refrigerant pressure at the entrance of the condensers and immediately before entrance of the expansion valve is the same.
- ii. Refrigerant pressure after expansion valve is the same as pressure at the evaporators.
- iii. The fluid maximum flow rate should be established manufacturers specification since most systems do not have refrigerant flow meters.
- iv. These measured parameters will assist in reading enthalpy and entropy of refrigerant from the property tables.

An energy auditor should be guided by a checklist while conducting the measurements. During the energy audit measurements should be done continuously for the whole operation cycle. In some cases, dynamics in operations will require that

measurements should be done for than one cycle. Table 2 presents a minimum guide of the information required to determine the COPs

Table 2

Parameter	Location	Data Source	Values	
Pressure	At point 2 after the compressor, denoted P_2 .	Measured		
	At point 4 after the expansion valve, denoted P_4	Measured		
Temperature	At point 1 before the compressor, denoted T_1	Measured		
	Condenser outlet at point 2, denoted T_2	Measured		
	At point 3 after the condenser, denoted T_3 ,	Measured		
	At point 4 after the expansion valve, denoted T_4	Measured		
Enthalpy	Inlet to condenser at point 2 or compressor outlet, denoted h_2	Read in the tables		
	Condenser outlet at point 3, denoted h_3	Read in the tables		
	Evaporator outlet or compressor inlet at point 1, denoted h_1	Read in the tables		
Compressor power consumption	Measured at the compressor power supply inlet.	Measured using a power meter		

Making reference to Figure 2, Heat (Q_{in}) absorbed by the refrigerant at the evaporators is calculated using equation 3.

$$Q_{in} = h_1 - h_3 \quad (3)$$

Ideal compressor (fluid power) input (W_{ip}) to the refrigerant is given by equation4.

$$W_{ip} = h_2 - h_1 \quad (4)$$

When determining the performance of a vapour compression cycle it is necessary to calculate the operating compressor efficiency η_{comp} . This is determined using equation 5.

$$\eta_{comp} = \frac{W_{ip}}{W_{in}} \quad (5)$$

Where:

W_{in} is the input electric power measured at the compressor.

The compressor efficiency provides an indication of how much energy is lost at the compressor or how much useful energy is absorbed by the refrigeration cycle from the main supply.

Ideal coefficient of performance (COP_{ip}) should also be calculated and compared with the real overall COP. This will assist in trying to establish the potential areas of inefficiencies or energy losses. Ideal coefficient of performance (COP_{ip}) is calculated using equation 6.

$$COP_{ip} = \frac{h_1 - h_4}{h_2 - h_1} \quad (6)$$

Real COP will be calculated using equation 7

$$COP_{real} = \frac{h_1 - h_4}{W_{measured}} \quad (7)$$

Example 1

In an energy audit of a water chiller system, the following was recorded as shown in Table 3.

Table 3:

Time (hr)	Ambient Temps C	Evaporator Temp Degree C	Condenser Temperature Degree C	Power Measurements (kW)	Chilled Water
--------------	--------------------	--------------------------------	--------------------------------------	-------------------------------	------------------

						Temperatures (degree C)
		T ₁	T ₂	T ₃		
0	22	-4	70	35	65.39	5
1	21	-4	70	35	68.11	5
2	21	-4	70	35	68.19	6
3	20	-5	70	33	68.90	6
4	19	-5	70	33	65.61	7
5	19	-5	65	33	61.29	7
6	18	-5	65	33	59.43	8
7	18	-5	64	33	58.45	8
8	17	-5	65	33	63.97	8
9	21	-5	65	33	60.04	9
10	23	-4	68	33	67.75	8
11	24	-4	69	34	66.88	8
12	26	-4	70	34	65.39	8
13	28	-4	70	34	69.67	9
14	29	-4	70	35	66.76	9
15	29	-4	70	35	68.14	10
16	29	-3	70	35	65.74	10
17	28	-3	70	35	67.14	8
18	28	-3	70	36	67.25	9
19	26	-3	70	35	67.25	7
20	26	-3	70	35	67.25	6
21	25	-3	70	35	67.35	7
22	24	-4	70	34	67.21	6
23	23	-4	70	34	67.62	7

Parameter	Value	Unit
Chilled water temperature	12 to 14	°C
Maximum cooling load	349.2	kW
Test COP	4.85	kW/kW
Maximum power input	119	kW
Maximum operations refrigerant flow rate	4000	kg/h
Maximum chilled water flow rate requirement	8.0	litres/s
Water pressure	8	Bars
Minimum chilled water operating temperature	9	°C

In this problem, the auditor should use the information to establish:

- i. ideal and real operating average COP;
- ii. ways of improving COP and establish your COP thereafter.

Ideal and Real COP

To determine ideal COP_{ip} , equation 6 is used. The enthalpy values h_1 , h_2 and h_3 will be obtained from steam and fluid property tables informed by the measured values T_1 , T_2 and T_3 .

Table 3

Time (hr)	Ambi ent Tem ps C	Evapor ator Temp C	Conden ser Temper ature		Enthalpies						
		T_1	T_2	T_3	h_2	h_{2f}	h_1	Q_{out} $=h_2-h_3$ kJ/ kg	$Q_{in}=$ h_1-h_3 kJ/kg	$W=$ h_2-h_1 kJ/kg	CO P_{ip}
0	22	-4	70	35	302.34	98.78	244.9	203.6	146.1	57.4	2.5
1	21	-4	70	35	302.34	98.78	244.9	203.6	146.1	57.4	2.5
2	21	-4	70	35	302.34	98.78	244.9	203.6	146.1	57.4	2.5
3	20	-5	70	33	302.34	95.81	244.1	206.5	148.3	58.2	2.5
4	19	-5	70	33	302.34	95.81	244.1	206.5	148.3	58.2	2.5
5	19	-5	65	33	296.85	95.81	244.1	201.0	148.3	52.7	2.8
6	18	-5	65	33	296.85	95.81	244.1	201.0	148.3	52.7	2.8
7	18	-5	64	33	295.75	95.81	244.1	199.9	148.3	51.6	2.9

8	17	-5	65	33	296.85	95.81	244.1	201.0	148.3	52.7	2.8
9	21	-5	65	33	296.85	95.81	244.1	201.0	148.3	52.7	2.8
10	23	-4	68	33	300.14	95.81	244.9	204.3	149.1	55.2	2.7
11	24	-4	69	34	301.24	97.31	244.9	203.9	147.6	56.3	2.6
12	26	-4	70	34	302.34	97.31	244.9	205.0	147.6	57.4	2.6
13	28	-4	70	34	302.34	97.31	244.9	205.0	147.6	57.4	2.6
14	29	-4	70	35	302.34	98.78	244.9	203.6	146.1	57.4	2.5
15	29	-4	70	35	302.34	98.78	244.9	203.6	146.1	57.4	2.5
16	29	-3	70	35	302.34	98.78	245.7	203.6	146.9	56.7	2.6
17	28	-3	70	35	302.34	98.78	245.7	203.6	146.9	56.7	2.6
18	28	-3	70	36	302.34	100.25	245.7	202.1	145.4	56.7	2.6
19	26	-3	70	35	302.34	98.78	245.7	203.6	146.9	56.7	2.6
20	26	-3	70	35	302.34	98.78	245.7	203.6	146.9	56.7	2.6
21	25	-3	70	35	302.34	98.78	245.7	203.6	146.9	56.7	2.6
22	24	-4	70	34	302.34	97.31	244.9	205.0	147.6	57.4	2.6
23	23	-4	70	34	302.34	97.31	244.9	205.0	147.6	57.4	2.6
Average	23.5	-4.0	68.8	34.2	301.01	97.545	244.9				2.6

The average hourly COPs for 24 hours were used to calculate the chillers ideal operation cycle COP, which is 2.6.

Note: It is prudent to calculate standard deviation of the measured COPs to test whether the average statistically represents all the measured values within the acceptable error limits. This concept will be discussed further in the 'measurement' volume.

Real operating COP was calculated from the total energy measured during the operation cycle. The real COP was calculated using equation 7 and the values are presented in Table 4.

Table 4: Representation of real COP calculations.

Hour	$Q_{in}=h_2-h_1$ kJ/kg	Refrigerant flow in kg/s	Q_{in} (kJ/s or kW)	Measured Power in fluid (kW)	Rated Compressor power	Real COP	Compressor loading (%)
0	146.12	1.11	162.35	65.39	72	2.48	90.82
1	146.12	1.11	162.35	68.11	72	2.38	94.60
2	146.12	1.11	162.35	67.97	72	2.39	94.40
3	148.30	1.11	164.78	69.12	72	2.38	96.00
4	148.30	1.11	164.78	68.90	72	2.39	95.69
5	148.30	1.11	164.78	59.43	72	2.77	82.54
6	148.30	1.11	164.78	61.29	72	2.69	85.13
7	148.30	1.11	164.78	58.19	72	2.83	80.82
8	148.30	1.11	164.78	59.69	72	2.76	82.91
9	148.30	1.11	164.78	63.97	72	2.58	88.85
10	149.09	1.11	165.65	62.89	72	2.63	87.35
11	147.59	1.11	163.99	69.10	72	2.37	95.97
12	147.59	1.11	163.99	68.19	72	2.40	94.70
13	147.59	1.11	163.99	65.39	72	2.51	90.82
14	146.12	1.11	162.35	69.67	72	2.33	96.77
15	146.12	1.11	162.35	66.76	72	2.43	92.72
16	146.91	1.11	163.23	67.21	72	2.43	93.35
17	146.91	1.11	163.23	65.74	72	2.48	91.30
18	145.44	1.11	161.59	67.14	72	2.41	93.26
19	146.91	1.11	163.23	67.25	72	2.43	93.41
20	146.91	1.11	163.23	67.25	72	2.43	93.41
21	146.91	1.11	163.23	67.25	72	2.43	93.41
22	147.63	1.11	164.03	68.29	72	2.40	94.84
23	147.59	1.11	163.99	67.21	72	2.44	93.35
Average						2.49	91.52

The real COP is always less than ideal COP. The ratio of real COP to ideal COP is the compressor efficiency which in this example is 95.8%. The auditor should compare the operating COPs (that is real and ideal COPs) to the rated COP to establish the overall system efficiency.

In this audit, the ratio of operating real COP to the rated COP is 51.56% while that of ideal is 53.6%. It is recommended that these ratios should be at least 70%. An exemption to this rule applies to HVACs that operate in extreme temperature and humid conditions.

In scenarios where this ratio is below 70%, the energy auditor should suggest and design ways of improving the COPs of the chiller.

Ways of improving COP

Some of the ways of improving the operating COP are:

Optimization of heat transfer at the condenser and evaporator	This can be achieved through scheduled maintenance. Regular cleaning of the evaporator and condenser heat transfer surfaces reduces the resistance to heat transfer from mediums or systems being cooled.
Thermal Storage	This can be achieved by enhancing automatic controls and running the chiller during colder hours to relatively lower temperatures below the minimum set point. Let us recall that the work required to cool space when the ambient temperature is low will be relatively lower. An air conditioner will work harder to cool space in a 28°C compared to 15°C.
Operate the evaporator at relatively higher temperature and the condenser at relatively lower temperature	Operating the evaporator at a higher temperature or condenser at a lower temperature will reduce the amount of work done by the compressors, hence increasing the operating COP of the chiller. Note: Before adjusting the evaporator or condenser temperature, the following conditions should be checked: • Design characteristic of the chiller • Temperature requirements of the systems being cooled • Ambient conditions.

Let us use example 2 to demonstrate the potential energy saving due to increasing evaporators operating temperatures. Table 6 shows the results of calculations after changing evaporator operation temperatures from -ve 4°C to +ve 4°C (Recall the operating chiller temperature was 9°C)

Table 6: Results of calculations after increasing evaporator operation temperatures from $-ve$ 4°C to $+ve$ 4°C

Time (h)	Evaporator Temp Degree C	h_1 at $-ve$ 4 degrees	h_1 at $+ve$ 4 degrees	h_1	h_3	Heat flow at evaporator (kJ/kg) ($-ve$ 4)	Heat flow at evaporator (kJ/kg) ($+ve$ 4)	h_1-h_4 (at $-ve$ 4)	h_1-h_4 (at $+ve$ 4)	Energy savings (kJ/kg)	Refrigerant Flow kg/s	Energy Savings in kW	Power Measurements (kW)
	T_4												
0	-4	244.90	249.43	29.8.4	98.78	146.12	150.65	53.45	48.92	4.53	1.11	5.03	65.39
1	-4	244.90	249.43	29.8.4	98.78	146.12	150.65	53.45	48.92	4.53	1.11	5.03	68.11
2	-4	244.90	249.43	29.8.4	98.78	146.12	150.65	53.45	48.92	4.53	1.11	5.03	68.19
3	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	68.90
4	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	65.61
5	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	61.29
6	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	59.43
7	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	58.45
8	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	63.97
9	-5	244.11	249.43	29.8.4	95.81	148.30	153.62	54.24	48.92	5.32	1.11	5.91	60.04
10	-4	244.90	249.43	29.8.4	95.81	149.09	153.62	53.45	48.92	4.53	1.11	5.03	67.75
11	-4	244.90	249.43	29.8.4	97.31	147.59	152.12	53.45	48.92	4.53	1.11	5.03	66.88
12	-4	244.90	249.43	29.8.4	97.31	147.59	152.12	53.45	48.92	4.53	1.11	5.03	65.39
13	-4	244.90	249.43	29.8.4	97.31	147.59	152.12	53.45	48.92	4.53	1.11	5.03	69.67
14	-4	244.90	249.43	29.8.4	98.78	146.12	150.65	53.45	48.92	4.53	1.11	5.03	66.76
15	-4	244.90	249.43	29.8.4	98.78	146.12	150.65	53.45	48.92	4.53	1.11	5.03	68.14
16	-3	245.69	249.43	29.8.4	98.78	146.91	150.65	52.66	48.92	3.74	1.11	4.16	65.74
17	-3	245.69	249.43	29.8.4	98.78	146.91	150.65	52.66	48.92	3.74	1.11	4.16	67.14
18	-3	245.69	249.43	29.8.4	10.0.3	145.44	149.18	52.66	48.92	3.74	1.11	4.16	67.25
19	-3	245.69	249.43	29.8.4	98.78	146.91	150.65	52.66	48.92	3.74	1.11	4.16	67.25
20	-3	245.69	249.43	29.8.4	98.78	146.91	150.65	52.66	48.92	3.74	1.11	4.16	67.25
21	-3	245.69	249.43	29.8.4	98.78	146.91	150.65	52.66	48.92	3.74	1.11	4.16	67.35

22	-4	244. 90	249. 43	29 8.4	97. 31	147.59	152.12	53. 45	48. 92	4.53	1.11	5.03	67.21
23	-4	244. 90	249. 43	29 8.4	97. 31	147.59	152.12	53. 45	48. 92	4.53	1.11	5.03	67.62
Average						147.32	151.88 5	53. 48	48. 92	4.56	1.11	5.07	65.87

Table 6 shows 8.53 % energy savings after increasing operations temperatures from –ve 4°C to +ve 4°C, this results into the reduction power demand by 5.07 kW. It can also be observed that heat flow at the evaporator increases by 3.097%. This implies the flow rate of water or, air -in case of air is used as a cooling media- should be increased to extract extra heat.

Example 1 is dealing with water chiller, we need calculated extra water flow rate and extra power required.

Change in mass flow rate of water is given by equation Eqn 7.

$$\Delta \dot{Q} = \Delta \dot{m}_w C_w \Delta T \quad (7)$$

$\Delta \dot{Q}$ = change in heat flow

$\Delta \dot{m}_w$ = change in heat flow

C_w = Specific heat capacity of water

ΔT = Change in temperature

From table 5, $\Delta \dot{Q} = 1.111 \text{ kg/s} \times (151.885 - 147.32) \text{ kJ/kg} = 5.0692 \text{ kJ/s}$

Then

$$\Delta \dot{m} = \frac{5.0692}{4.184 \times (23.5 - 9)} = 0.0836 \text{ kg/s}$$

Assuming water density is 1000kg/m³, this volume flow rate = $0.0836 \times 10^{-3} \text{ m}^3/\text{s}$

The increase in water pumping power demand = $8 \times 100,000 \times 0.0836 \times 10^{-3} = 66.85 \text{ W}$ (or $66 \times 10^{-3} \text{ kW}$).

This is very small compared to 5.07 kW reduction in refrigerant compressor power.

This energy conservation measure has zero financial investment!

The same process can be used to analyse and calculate power demand reduction in case of reduction in condenser operating temperatures.

NOTE: Temperature reduction or increase in evaporator should not just be recommended as a *“rule of thumb”* but should be done after analysis. Like in example 1 the main reason of increasing the evaporator temperature was after checking chilled water is required at 9°C. A temperature difference of 5°C is good enough to facilitate heat transfer.

Heating Ventilation and Air Conditioning (HVAC)

To carry out an energy audit of a HVAC system, it is important to understand its main components and the energy flow therein. Figure 1 shows a typical HVAC system.

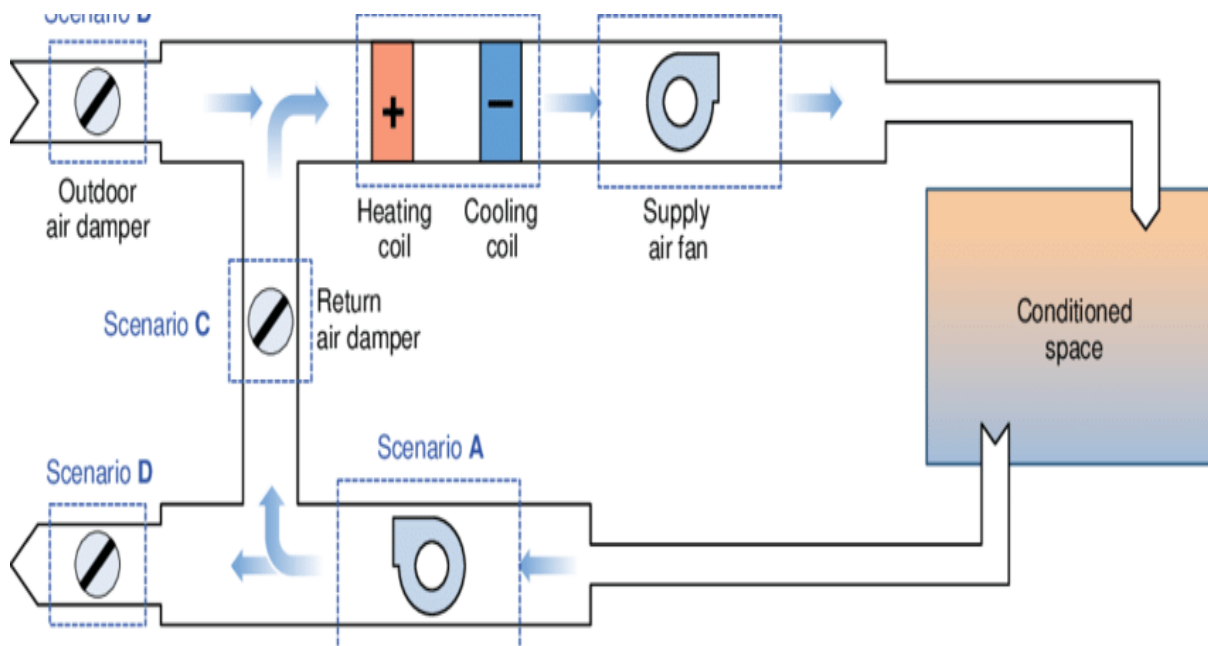


Figure 1: HVAC System components and Air flow

The main purpose of a HVAC system is to condition air for human comfort, storage of goods and manufacturing processes. This is achieved in the conditioned space depicted in Figure 1. Air conditioning involves cooling, heating, elimination of particulate matter, and regulating humidity and CO₂ levels. These functions are dependent on specific applications in the conditioned space. For example, in an

operation theatre or a data centre, air is conditioned through cooling or heating, regulating the relative humidity and removing particulate matter.

Several components are used to achieve the air conditioning parameters and are described as follows

Air inducing system	It mainly consists of fans, ducts and air dampers. The fans are driven by electrical motors and in some rare cases by internal combustion engines. The system shown in Figure 1 has two fans. However, the number of fans in a system is dependent on its size and the configuration.
Cooling mechanism	Cooling in a HVAC system is mainly achieved by the vapour compression cycle, cooling towers and in some cases natural ventilation.
Heating Mechanism	Air in a HVAC system can be heated using electric heating elements, steam heaters, heat pumps or solar heaters.
Humidification mechanism	In this process, water is induced into air to increase humidity. This can be done through introduction of steam and atomized water.
Filtration Mechanism	Particulate matter is removed from the conditioned air using filters, and in some cases, cyclones.

Note: Cooling coils, heating coils, air delivery fans and filters can be compartmentalized and referred to as air handling units (AHU).

Cooling and heating systems are the main consumers of energy in an HVAC system. Their design and mode of operation affects the energy efficiency of the system. This section of the guidebook will focus on the vapour compression refrigeration-based HVAC systems. Electric heaters, water-steam boilers, cooling towers and fans will be handled in other sections of this guidebook.

Types of HVAC systems

HVAC systems are classified according to the method of operation. The method of operation mainly involves the type and size of compressor used and cooling method. These systems can be classified as:

- i. Non- ducted Split Systems.

They are relatively small compact units, mostly used in homes, offices and small data centres. They employ a vapour compression cycle for cooling or heating. They are also called air to air split systems. Figure 3 shows a picture of a non-ducted split system.

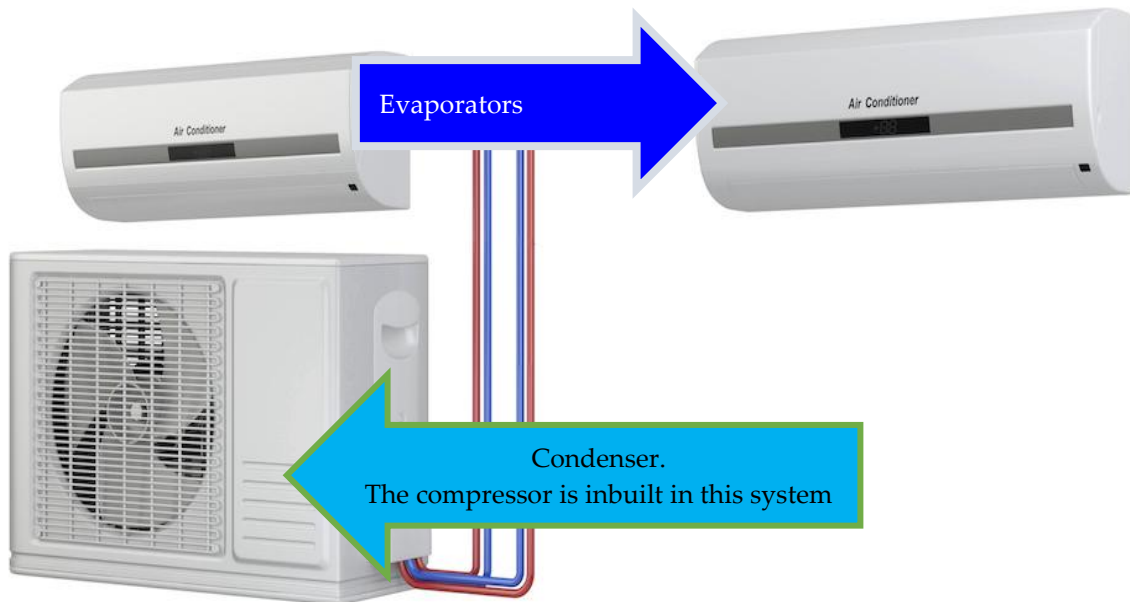
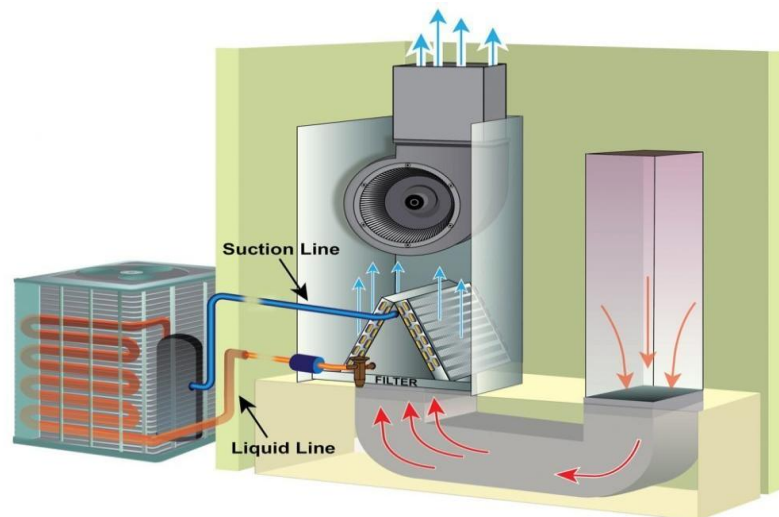


Figure 3: Non-ducted split conditioning system.

These systems can be used for both heating and cooling. When used for heating they are referred to heat pumps.

ii. Ducted air conditioning systems

They are relatively larger than the non-ducted split systems. Unlike the split systems, the ducted systems convey conditioned air via a duct. The cooling or heating from the vapor compression cycle takes place within the duct, where the evaporator coils are placed. This type of system can be centralized, serving multiple rooms. Figure 4 shows ducted air conditioning system.



conditioning system.

Figure 4: Ducted Air-to-to air split conditioning system.

Then there slightly larger units which employ screw or reciprocating compressors, with air cooled condensers fitted with up to 10 cooling fans depending on the size.

iii. Water chiller systems

Water chiller systems are relatively larger than ducted system. They are used in situation where:

- i. The evaporator coils cannot be installed near the conditioned space due to design issues like: lack of space, noise, economics of scale and aesthetics.
- ii. Where many spaces are supplied by a central system
- iii. Relatively heavy cooling loads.

In water chillers, water is cooled at the evaporator coils and then transported to the conditioned space. Water is preferred than air because of its high specific heat capacity. In cases of glycol is added to water to improve its heat capacity by reducing freezing point, especially when thermal storage is necessary.

Figures 5 and 6 shows examples of water chillers.



Figure 5: Water chiller connection



Figure 6: Water Chiller photo

3. Processes in HVAC Systems

HVAC systems have two major process processes which should be understood by the energy auditor since they instrumental in determining their operations and energy performance. These are:

- i. Vapour compression cycle, and
- ii. Psychrometric processes

Vapour Compression Cycle

In a vapour-compression refrigeration cycle a low boiling fluid, referred to as a refrigeration, is used to extract heat from a low-temperature region and release it to higher-temperature region. In order to release heat to a higher, the refrigerant pressure should be raised several times above atmospheric temperature.

A compressor is used to raise refrigerant pressure above atmospheric. Compressor power is the main energy input to the refrigeration cycle. This is the energy responsible for moving heat from low temperature region to high temperature region. A summary of the operation of a refrigeration cycle is shown in figure 7 and 8.

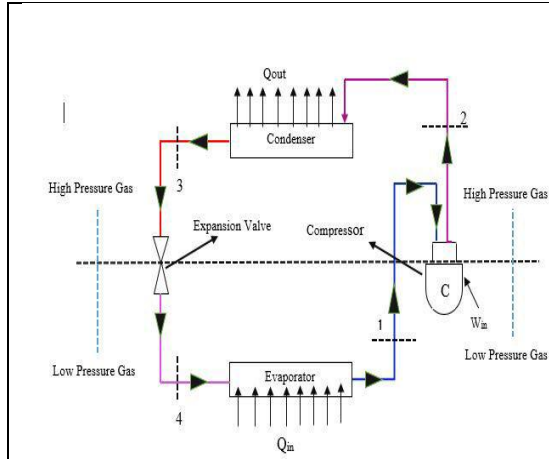


Figure 7: Heat and work flow in a refrigeration cycle

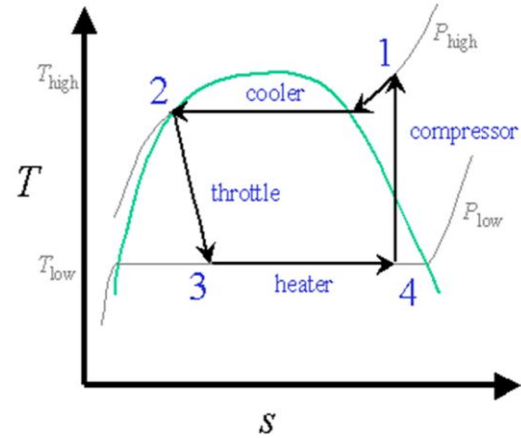


Figure 8: Refrigeration cycle in Temperature (T) – Entropy (S) diagram

The performance of the refrigeration cycle is measured by the amount of heat removed from the lower temperature region per unit of work or power input to the system the compressor. The ratio of heat removed from the cold area to power input to the cycle is referred to as coefficient of performance (COP) or energy efficiency ratio (EER), depending on units used. This can be considered as the “energy efficiency” refrigeration cycle. The performance of the refrigeration cycle is normally affected by heat transfers at the condenser, the evaporators and efficiency of the compressors.

$$COP = \frac{Q_{in}}{W_{in}} \quad (1)$$

Where

COP = coefficient of performance

Q_{in} = heat drawn from low temperature area to the refrigeration cycle

W_{in} = power input to the refrigeration cycle

When units of energy, that Q_{in} and W_{in} are the same the ratio is called COP. But EER is the ratio of when units of Q_{in} are in joules (J) or British Thermal Units (BTU) depending on the country or region and units of W_{in} are in watts (W).

$$EER = \frac{Q_{in} \text{ (in Joules or BTU)}}{W_{in} \text{ (in watts)}} \quad (2)$$

The performance of a refrigeration cycle can be established during an energy audit. During the energy audit measurements should be done continuously for the whole

operation cycle. In some cases, dynamics in operations will require that measurements should be done for at least 14 days in order to cover days of the week.

The aim of energy efficiency program is to ensure the COP (EER) is as large as possible during operations. This can be done by reducing W_{in} for the same Q_{in} , by improving heat transfers at both condensers and evaporators.

PSYCHROMETRICS

To establish the cooling load of a space, like, office space, go down, data centre, cinema hall, theatre or mall, it is good to take into considerations the thermodynamic air properties requirements of the space and external conditions. In most cases the thermodynamic air properties are mainly characterised by the water moistures content, carbon dioxide levels and particulate matter properties. These properties will determine cooling load and hence the amount cooling energy required.

This section will mainly dwell in calculating the cooling load and energy required caused by the change in air temperature and humidity as it is transferred from one system or state to another.

In air condition system air undergoes several processes which can be traced in the psychrometric chart. In these processes cooling load is established by calculating the change in enthalpy between any given states, that is initial and final states. Figure 11 shows the processes undergone by air during air-conditioning.

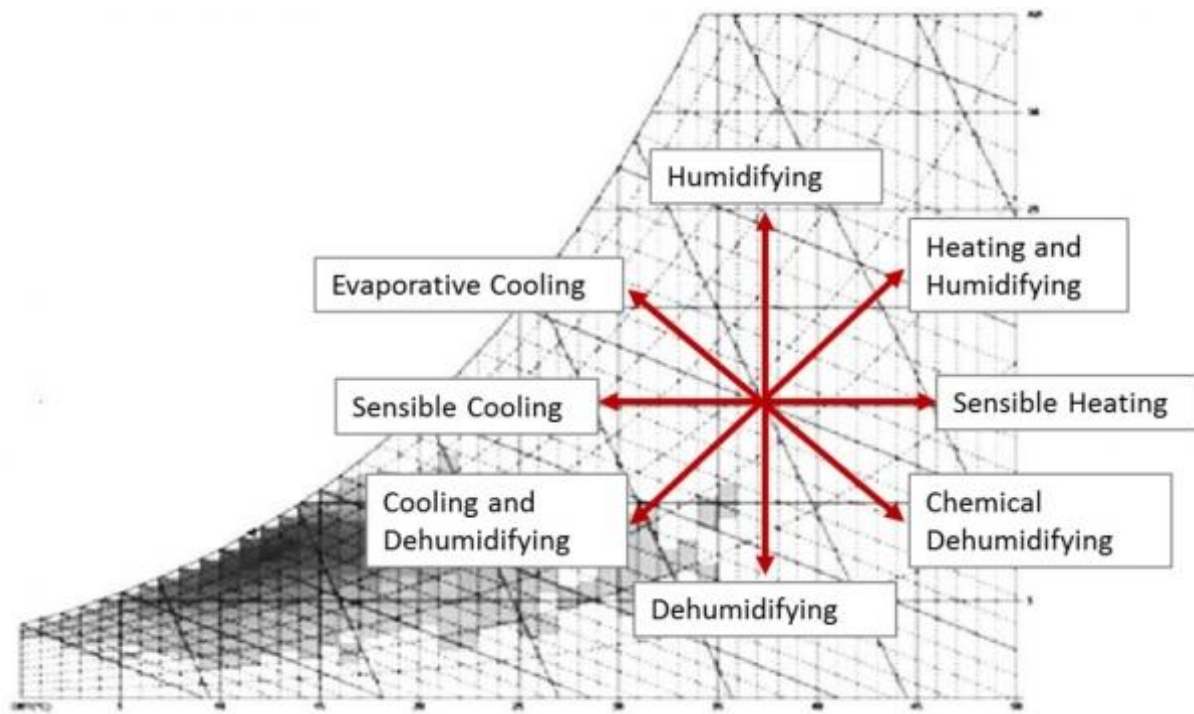


Figure 11: Processes undergone by air during air conditioning process.

Processes shown in Figure 11 are determined by the requirements of the conditioned space or system and ambient conditions. These conditions are mainly expressed in terms of temperatures and relative humidity, since most instruments are designed to measure them.

Even though it is good enough to use parameters from psychrometric developed by considering atmospheric conditions at the sea level to calculate cooling load requirements, you can accurately get these parameters using online calculators for a facility in any altitude.

When auditing an air conditioning systems, the following parameters are supposed to be measured. These are:

- i. Temperature of ambient air
- ii. Relative humidity of ambient air
- iii. Temperature of the conditioned space or system
- iv. Relative humidity of the conditioned space or system
- v. Power demand of the water chiller
- vi. Parameters mentioned in example 1.
- vii. Chilled water flow rate. If a water chiller is used
- viii. Pressure of the chilled water
- ix. Condenser cooling water flow rate. If the chiller is water cooled

- x. Condenser cooling water pressure. If the chiller is water cooled
- xi. Condenser cooling air flow rate. If the chiller is air cooled
- xii. Condenser cooling air temperature. If the chiller is air cooled
- xiii. Chilled water pump power demand
- xiv. Condenser cooling water pump power demand
- xv. Condenser cooling air fans power demand
- xvi. Air handling unit (AHU) fans power demand
- xvii. AHU cooling air flow rate
- xviii. AHU cooling air temperature and humidity. That is after it has passed through cooling coils
- xix. AHU air pressure difference. That is difference of pressure between inlet air and air after cooling coils.

For accurate analysis during an energy audit. These parameters should be measure over the operation cycle of the water chiller system. As a rule of the thumb, the minimum duration of measurements should be at least 24 hours. Although the measurements period will depend on the system and facility. For example, in a data centre the operation cycle should be at least 14 days.

The following are different air conditioning processes.

i. Sensible heating and cooling

This is situation where heat is added into air without change in the humidity ratio. In this process only the temperature of air increases or decreases.

The cooling load or heating load, in case where temperature needs to be increased is given by equation Eqn 8.

$$Q_l = \dot{m}_a C_a (T_2 - T_1) \quad (8)$$

Where:

Q_l = cooling load

$\dot{m}_a$ = mass flow of air

C_a = Specific heat capacity of air at constant of air

T_1 = initial temperature of air

T_2 = Final temperature of air

In the case of sensible heating a cooling air is delivered into the conditioned space using a fans. These fans driven by a motor. The amount of electrical power required to run the fans and motor is given by equation Eqn 9.

$$E_p = \frac{\Delta P_f \times V_{af}}{\eta_f \times \eta_m} \quad (9)$$

Where:

ΔP_f = change in pressure across the fan

V_{af} = air volumetric flow rate

η_f = fan efficiency

η_m = motor efficiency

where air volumetric flow rate is given by equation Eqn 10.

$$V_{af} = \frac{\dot{m}_a}{\rho_a} \quad (10)$$

Where

ρ_a = density of air at that particular temperature.

In most cases there are instruments, called air flow meters, which can measure air volumetric flow rate directly. In this case heat (Q_l) removed by air from the conditioned space can be calculated using equation Eqn 11.

$$Q_l = 1.2 \times V_{af} \times (T_2 - T_1) \quad (11)$$

Note in equation Eqn 11 the units of flow rate V_{af} should be in litres per second so that units of Q_l are in watts (W).

Assuming Q_l is the cooling load the cooling load then equation Eqn 11 can be used to calculate the required volumetric air flow rate V_{af} of air required to maintain the space at temperature T_2 , assuming ambient temperature is T_1 .

During an energy audit of a fan system electrical power demand should be measured during the system operation cycle so that efficiency of fan system can be established. Full details of how to audit a fan duct system will be discussed in another section of this guide book, that is “*auditing of fans system*”.

ii. Humidification and Dehumidification

Humidification is the process of adding water moisture to air in the air conditioned space, while dehumidification is removal of water moisture to

the air conditioned space, without change in temperature. *Why do add or remove water moisture from the air conditioned space?*

These process are directly opposite in the psychrometric chart. To achieve any of these two process energy is required. Addition of water to the air conditioned space can be for example achieved by pressuring water and pushing it through spray nozzles or by heating water to get steam the release it to the space. To remove water moisture from air in the air-conditioned space can be achieved by passing moist-air through a water absorbing material.

The amount of water moisture (w) to be removed or added from the cubic metre (m^3) air can be calculated using equation Eqn 12.

$$w = \rho_{a1}(W_2 - W_1) \quad (12)$$

Where

ρ_{a1} = Density of air at state 1(initial state)

W_1 = Humidity ratio (in kgw/kga) at initial state

W_2 = Humidity ratio (in kgw/kga) at final state

Total amount of water added or removed in a given space will depend on the size of the space or defined amount of air require per unit time.

iii. Heating and humidification/cooling and dehumidification.

The processes described in (i) and (ii) very are in practical real live situation and can be described as ideal states. This is because in real situation the ambient conditions, temperature and humidity keep on changing from time to time during the time day and during the seasons.

In trying to get the right set point of the system in the air-conditioned space of system external air will be required to go through a combination of different processes. For example, if air is required to be supplied in an operation theatre at temperature of 24°C, relative humidity (RH) of 50%, and external air is at a temperature of 19°C, and relative humidity of 80%. It means that this air will require to go through several processes. That is, remove water moisture from air then heat he air to from 19°C to 24°C. The process of removing water moisture from air can be done in several ways. These are chemical absorption or cooling air up to the dew-point

temperature of the second state, that is temperature of 24°C and RH 50%. *Considering that air is being supplied to an operation theatre, which method you prefer?*

There are situations where cooling and dehumidification is required. For example, if the set point of an air-conditioned space is temperature of 20°C, RH 55% and air is delivered from external sources where the average ambient conditions are temperature are 28°C and RH is 75%.

The other scenario is where the set point of a conditioned space is 26°C and RH is 65%, while ambient conditions are temperature 15°C and RH 35%. *What process is this? What if the set condition is temperature 17°C, RH 80% and average external conditions are temperature 26°C, RH 40%?*

The good thing is that in thermodynamic process it does not matter the steps you take, but what matters is the initial and the final stages.

In these cases, heat added to the system is given by equation Eqn 13.

$$Q_l = 1.2 \times V_{af} \times (h_2 - h_1) \quad (13)$$

Note in equation Eqn 13 the units of flow rate V_{af} should be in litres per second so that units of Q_l are in watts (W). This is an example of cooling, dehumidification and heating.

During an energy audit the main aim is to establish the optimum amount of electrical power required to drive the amount air to the conditioned space. Equation Eqn 9 can be used to find the optimum amount of power required for a given situation of operation.

Example 2 can be used to illustrate an energy audit in an air conditioning system.

Example 2:

During an energy audit of an air conditioning system the following data was correct through measurements and recorded in Table 6:

Table 6: Chiller Energy Data

Time (Hour)	Set temp at condition space	Set relative humidity at condition space (in %)	Ambient Temp in degrees	Ambient Relative Humidity (%)	Air Exhaust Temp degree	Air Flow Rate from AHU to conditioned space (cubic metres /s)	Chiller water flow rate Water flow l/s	Water to HVAC for Chiller temp in degrees C	Water Temp in degrees from AHU	Power measurement (kW)	Change pressure the fan (Pa)	Measured fan power Electrical power (kW)
0	19	50	18	84	23.1	60.83	39.85	7	10.9	426.0	159.00	33.25
1	19	50	18	84	22.5	60.83	39.85	7	10.9	464.3	161.00	33.67
2	19	50	18	83	20.9	60.83	39.85	6	9.8	468.6	157.00	32.81
3	19	50	18	83	20.0	60.83	39.85	6	9.8	451.6	158.00	33.04
4	19	50	18	83	19.4	60.83	39.85	6	9.8	515.5	161.00	33.65
5	19	50	17	82	18.2	60.83	39.85	6	8.6	502.7	162.00	34.86
6	19	50	17	82	20.6	60.83	39.85	6	8.6	438.8	157.00	33.81
7	19	50	18	97	22.9	60.83	39.85	8	13.8	451.6	153.00	30.98
8	19	50	18	92	20.8	60.83	39.85	7	12.0	455.8	156.00	32.67
9	19	50	20	85	25.2	60.83	39.85	7	13.4	426.0	158.00	33.02
10	19	50	21	78	27.7	60.83	39.85	7	13.4	464.3	159.00	32.23
11	19	50	23	70	28.2	60.83	39.85	8	15.2	468.6	157.00	32.86
12	19	50	24	64	29.1	60.83	39.85	8	15.2	451.6	158.00	33.02
13	19	50	25	61	28.5	60.83	39.85	8	15.7	472.9	155.00	32.59
14	19	50	25	61	28.5	60.83	39.85	8	15.7	506.9	156.00	32.60
15	19	50	25	63	29.8	60.83	39.85	8	16.1	438.8	154.00	32.18
16	19	50	24	67	27.0	60.83	39.85	8	15.8	451.6	158.00	35.02
17	19	50	23	82	27.3	60.83	39.85	8	17.6	455.8	151.00	30.56
18	19	50	21	87	21.8	60.83	39.85	8	15.9	438.8	160.00	34.44
19	19	50	21	86	20.1	60.83	39.85	8	15.7	451.6	163.00	34.92
20	19	50	20	84	20.2	60.83	39.85	7	13.2	455.8	166.00	35.61
21	19	50	19	84	20.3	60.83	39.85	6	11.0	447.3	161.00	34.60
22	19	50	19	84	20.3	60.83	39.85	6	11.0	464.3	163.00	35.07
23	19	50	19	84	19.7	60.83	39.85	6	11.0	468.6	162.00	33.86
Average	19	50	20	80	23.4	60.83	Total	7.08	12.9	459.90	158.54	33.39

Fan motor ratings are: 30 kW, Efficiency 91.7% and speed 1000 rev/min.

Calculate

- Quantity of heat, in kWh, transferred from air to cooling water at the AHU unit to achieve desired set point, that is 19°C and relative humidity (RH) 50%, of conditioned space (*use average values over the 24 hours*).

Use equation Eqn 13:

$$Q_l = 1.2 \times V_{af} \times (h_2 - h_1) \quad (13)$$

First establish the values of h_1 and h_2 from the psychrometric chart and use their average over 24 hours. Table 7 shows the values of h_1 and h_2 .

Table 7: Shows the values of h_1 and h_2

Time (Hour)	Set temp at condition space	Set relative humidity at condition space (in %)	Enthalpy (h) of conditioned space (kJ/kg) (h ₁)	Ambient Temp in degrees	Ambient Relative Humidity (%)	Ambient Enthalpy (h) in kJ/kg (h ₂)
0	19	50	40.67	18	84	52.35
1	19	50	40.67	18	84	52.35
2	19	50	40.67	18	83	51.94
3	19	50	40.67	18	83	51.94
4	19	50	40.67	18	83	51.94
5	19	50	40.67	17	82	48.41
6	19	50	40.67	17	82	48.41
7	19	50	40.67	18	97	57.8
8	19	50	40.67	18	92	55.7
9	19	50	40.67	20	85	59.58
10	19	50	40.67	21	78	59.63
11	19	50	40.67	23	70	62.25
12	19	50	40.67	24	64	62.14
13	19	50	40.67	25	61	63.62
14	19	50	40.67	25	61	63.62
15	19	50	40.67	25	63	64.92
16	19	50	40.67	24	67	63.97
17	19	50	40.67	23	82	69.17
18	19	50	40.67	21	87	64.19
19	19	50	40.67	21	86	63.68
20	19	50	40.67	20	84	59.1
21	19	50	40.67	19	84	55.67
22	19	50	40.67	19	84	55.67
23	19	50	40.67	19	84	55.67
Average	19	50	40.67	20	80	58.07

$$Q_i = \{1.2 \times 60.83 \times 1000 \times (58.07 - 40.67)\} / 1000 = 1,270.1304 \text{ kW}$$

$$\text{Heat energy absorbed in 24 hours} = 1,270.1304 \times 24 = 30,483.13 \text{ kWh}$$

Heat absorbed by water to from air at AHU unit (*use average values over the 24 hours*).
(V_{wf} in l/s)

$$Q_{water} = V_{wf} \times 4.2 \times \Delta T$$

$$\text{Where, } \Delta T = (T_{ahu} - T_{chw})$$

$$Q_{water} = 39.85 \times 4.2 \times 5.82 = 974.0934 \text{ kW}$$

Heat energy absorbed in 24 hours = $974.0934 \times 24 = 23,378.2416 \text{ kWh}$

Heat transfer efficiency of the AHU unit (use average values over the 24 hours

Heat transfer efficiency = $Q_{\text{water}} / Q_{\text{air}} = 23,378.2416 / 30,483.13 = 76.69\%$

The quantity of heat in kWh extracted from the conditioned space in 24 hours (use average values over the 24 hours).

$Q_{\text{air}} = A_{\text{fr}} \times 1.2 \times \Delta T$ watts

= $\{60,830 \times 1.2 \times (23.4-19)\} / 1000 = 321.1824 \text{ kW}$

Heat absorbed in 24 hours = $321.1824 \times 24 = 7,708.3776 \text{ kWh}$

This is the cooling load of the room.