

## UNIT ! – INTRODUCTION

Refrigeration deals with cooling of bodies or fluids to temperatures lower than those of surroundings. This involves absorption of heat at a lower temperature and rejection to higher temperature of the surroundings. In olden days, the main purpose of refrigeration was to produce ice, which was used for cooling beverages, food preservation and refrigerated transport etc. Now-a-days refrigeration and air conditioning find so many applications that they have become very essential for mankind. The most important applications of refrigeration is in cooling and dehumidification as required for summer air conditioning.

### APPLICATIONS

The major applications of refrigeration can be grouped into following four major equally important areas.

1. Food processing, preservation and distribution
2. Chemical and process industries
3. Special Applications
4. Comfort air-conditioning

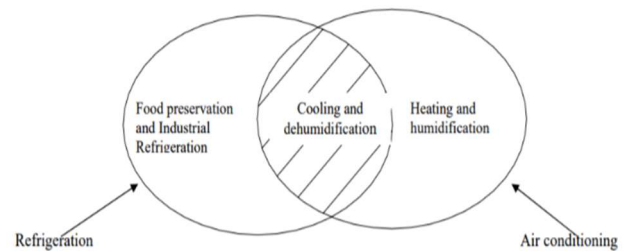


Fig.3.1. Relation between refrigeration and air conditioning

Special applications include Cold Treatment of Metals, Medical, Ice Skating Rinks, Construction, Desalination of Water, and Ice Manufacture

Refrigeration and air conditioning involves various processes such as **compression, expansion, cooling, heating, humidification, de-humidification, air purification, air distribution** etc. In all these processes, there is an exchange of mass, momentum and energy. All these exchanges are subject to certain fundamental laws

### IMPORTANT TERMS AND LAWS

#### SYSTEM, SURROUNDINGS AND BOUNDARY

Thermodynamics is the study of energy interactions between systems and the effect of these interactions on the system properties. Energy transfer between systems takes place in the form of heat and/or work. Thermodynamics deals with systems in equilibrium.

A **thermodynamic system** is defined as a quantity of matter of fixed mass and identity upon which attention is focused for study. In simple terms, a system is whatever we want to study. A system could be as simple as a gas in a cylinder or as complex as a nuclear power plant. Everything external to the system is the **surroundings**. The system is separated from the surroundings by the **system boundaries**.

Thermodynamic systems can be further classified into

- Closed systems,
- Open systems and
- Isolated systems.

A control volume, which may be considered as an **open system**, is defined as a specified region in space upon which attention is focused. The control volume is separated from the surroundings by a control surface. Both

mass and energy can enter or leave the control volume. In case of **closed system** this mass transfer is not possible. Whereas in case of **isolated system** both mass and energy transfer is not possible.

## PROCESS AND CYCLE

A process is defined as the path of thermodynamic states which the system passes through as it goes from an initial state to a final state. In refrigeration and air conditioning one encounters a wide variety of processes. Understanding the nature of the process path is very important as **heat** and **work** depend on the path. A system is said to have undergone a **cycle** if beginning with an initial state it goes through different processes and finally arrives at the initial state

## HEAT AND WORK

**Heat** is energy transferred between a system and its surroundings by virtue of a temperature difference only. The different modes of heat transfer are:

- Conduction,
- Convection and
- Radiation.

Heat is a way of changing the energy of a system. Any other means for changing the energy of a system is called **work**. We can have push-pull work (e.g. in a piston-cylinder, lifting a weight), electric and magnetic work (e.g. an electric motor), chemical work, surface tension work, elastic work, etc.

Mechanical modes of work: In mechanics work is said to be done when a force 'F' moves through a distance 'dx'. When this force is a mechanical force, we call the work done as a mechanical mode of work. The classical examples of mechanical mode of work are:

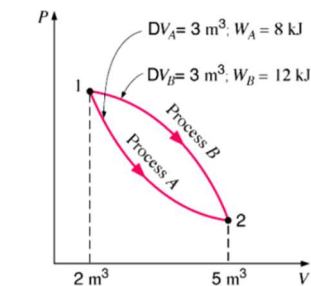


Fig. 4.1. Difference between point and path functions

1. Moving system boundary work
2. Rotating shaft work
3. Elastic work, and
4. Surface tension work

$$W_2 = \int_1^2 p \cdot dV$$

where 'p' is the pressure acting on the system boundary and 'dV' is the differential volume. It is assumed that the process is carried out very slowly so that at each instant of time the system is in equilibrium. Typically such a process is called a **quasi-equilibrium process**. For rigid containers, volume is constant, hence moving boundary work is zero in this case. For other systems, in order to find the work done one needs to know the relation between pressure p and volume V during the process.

### Sign convention for Work and Heat Transfer:

Most thermodynamics books consider the work done by the system to be positive and the work done on the system to be negative.

The heat transfer to the system is considered to be positive and heat rejected by the system is considered to be negative.

## PATH AND POINT FUNCTIONS

**Path function** depends on history of the system (or path by which system arrived at a given state). **Examples** for path functions are work and heat.

**Point function** does not depend on the history (or path) of the system. It only depends on the state of the system. Examples of point functions are: temperature, pressure, density, mass, volume, enthalpy, entropy, internal energy etc.

Path functions are not properties of the system, while point functions are properties of the system. Change in point function can be obtained by from the initial and final values of the function, whereas path has to be defined in order to evaluate path functions.

## PROPERTY

A property is any characteristic or attribute of matter, which can be evaluated quantitatively. The amount of energy transferred in a given process, work done, energy stored etc. are all evaluated in terms of the changes of the system properties. A thermodynamic property depends only on the state of the system and is independent of the path by which the system arrived at the given state. Hence all thermodynamic properties are point functions. Thermodynamic properties can be either **intensive** (independent of size/mass, e.g. temperature, pressure, density) or **extensive** (dependent on size/mass, e.g. mass, volume)

Thermodynamic properties relevant to refrigeration and air conditioning systems are temperature, pressure, volume, density, specific heat, enthalpy, entropy etc. It is to be noted that heat and work are not properties of a system.

## LAWS

**Conservation of Mass** is a fundamental concept, which states that mass is neither created nor destroyed.

**The Zeroth law of Thermodynamics** states that when two systems are in thermal equilibrium with a third system, then they in turn are in thermal equilibrium with each other. This implies that some property must be same for the three systems. This property is temperature. Thus this law is the basis for temperature measurement. Equality of temperature is a necessary and sufficient condition for thermal equilibrium, i.e. no transfer of heat.

**The First law of Thermodynamics** is a statement of law of conservation of energy. It states that energy can neither be created nor be destroyed but can be transferred from one form to the other. Also, according to this law, heat and work are interchangeable. Any system that violates the first law (i.e., creates or destroys energy) is known as a **Perpetual Motion Machine** (PMM) of first kind. For a system undergoing a cyclic process, the first law of thermodynamics is given by:

$$\oint \delta Q = \oint \delta W$$

where  $\oint \delta Q$  = net heat transfer during the cycle  
 $\oint \delta W$  = net work transfer during the cycle

$$\oint (\delta Q - \delta W) = 0$$

This implies that  $(\delta Q - \delta W)$  must be a point function or property of the system. This property is termed as *internal energy*,  $U$ . Mathematically, internal energy can be written as:

$$dU = \delta Q - \delta W$$

The internal energy of a system represents a sum total of all forms of energy viz. thermal, molecular, lattice, nuclear, rotational, vibrational etc.

### Clausius' statement of Second law

It is impossible to transfer heat in a cyclic process from low temperature to high temperature without work from external source.

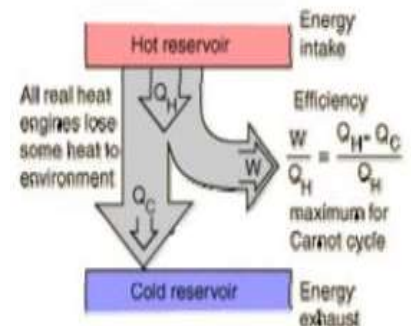
### Kelvin-Planck statement of Second law

It is impossible to construct a device (engine) operating in a cycle that will produce no effect other than extraction of heat from a single reservoir and convert all of it into work. Mathematically, Kelvin-Planck statement can be written as:

$$W_{\text{cycle}} \leq 0 \text{ (for a single reservoir)}$$

### Reversible and Irreversible Processes

A process is **reversible** with respect to the system and surroundings if the system and the surroundings can be restored to their respective initial states by reversing the direction of the process, that is, by reversing the heat transfer and work transfer. The process is **irreversible** if it cannot fulfill this criterion.



### HEAT ENGINES, REFRIGERATORS, HEAT PUMPS:

A **Heat Engine** may be defined as a device that operates in a thermodynamic cycle and does a certain amount of net positive work through the transfer of heat from a high temperature body to a low temperature body. **Example:** A steam power plant

A **Refrigerator** may be defined as a device that operates in a thermodynamic cycle and transfers a certain amount of heat from a body at a lower temperature to a body at a higher temperature by consuming certain amount of external work. **Example:** Domestic refrigerators and room air conditioners.. In a refrigerator, the required output is the heat extracted from the low temperature body.

A **Heat Pump** is similar to a refrigerator, however, here the required output is the heat rejected to the high temperature body.

### CARNOT'S THEOREMS FOR HEAT ENGINES:

**Theorem 1:** It is impossible to construct a heat engine that operates between two thermal reservoirs and is more efficient than a reversible engine operating between the same two reservoirs.

**Theorem 2:** All reversible heat engines operating between the same two thermal reservoirs have the same thermal efficiency.

The two theorems can be proved by carrying out a thought experiment and with the help of second law. Carnot's theorems can also be formed for refrigerators in a manner similar to heat engines.

**Carnot Efficiency:** The Carnot efficiencies are the efficiencies of completely reversible cycles operating between two thermal reservoirs. According to Carnot's theorems, for any given two thermal reservoirs, the Carnot efficiency represents the maximum possible efficiency.

Thermal efficiency for a heat engine,  $\eta_{HE}$  is defined as:

$$\eta_{HE} = \frac{W_{cycle}}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

where  $W_{cycle}$  is the net work output,  $Q_C$  and  $Q_H$  are the heat rejected to the low temperature reservoir and heat added (heat input) from the high temperature reservoir, respectively.

It follows from Carnot's theorems that for a reversible cycle ( $\frac{Q_C}{Q_H}$ ) is a function of temperatures

of the two reservoirs only. i.e.  $\frac{Q_C}{Q_H} = \phi(T_C, T_H)$ .

If we choose the absolute (*Kelvin*) temperature scale then:

$$\frac{Q_C}{Q_H} = \frac{T_C}{T_H}$$

hence,  $\eta_{Carnot, HE} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_C}{T_H}$

The efficiency of refrigerator and heat pump is called as Coefficient of Performance (COP). Similarly to heat engines, Carnot coefficient of performance for heat pump and refrigerators  $COP_{HP}$  and  $COP_R$  can be written as

$$\begin{aligned} COP_{Carnot, HP} &= \frac{Q_H}{W_{cycle}} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C} \\ COP_{Carnot, R} &= \frac{Q_C}{W_{cycle}} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C} \end{aligned} \quad (4.15)$$

where

- $W_{cycle}$  = work input to the reversible heat pump and refrigerator
- $Q_H$  = heat transferred between the system and the hot reservoir
- $Q_C$  = heat transferred between the system and cold reservoir
- $T_H$  = temperature of the hot reservoir
- $T_C$  = temperature of the cold reservoir

**Third law of thermodynamics:**

This law gives the definition of absolute value of entropy and also states that absolute zero cannot be achieved. Another version of this law is that "the entropy of perfect crystals is zero at absolute zero". This statement is attributed to Plank. This is in line with the concept that entropy is a measure of disorder of the system.

If ' $\omega$ ' is the probability of achieving a particular state out of a large number of states; then entropy of the system is equal to  $\ln(\omega)$ . The transitional movement of molecules ceases at absolute zero and position of atoms can be uniquely specified. In addition, if we have a perfect crystal, then all of its atoms are alike and their positions can be interchanged without changing the state. The probability of this state is unity, that is  $\omega = 1$  and  $\ln(\omega) = \ln(1) = 0$

For imperfect crystals however there is some entropy associated with configuration of molecules and atoms even when all motions cease, hence the entropy in this case does not tend to zero as  $T \rightarrow 0$ , but it tends to a constant called the entropy of configuration.

The third law allows absolute entropy to be determined with zero entropy at absolute zero as the reference state. In refrigeration systems we deal with entropy changes only, the absolute entropy is not of much use. Therefore entropy may be taken to be zero or a constant at any suitably chosen reference state.

Another consequence of third law is that absolute zero cannot be achieved. One tries to approach absolute zero by magnetization to align the molecules. This is followed by cooling and then demagnetization, which extracts energy from the substance and reduces its temperature. It can be shown that this process will require infinite number of cycles to achieve absolute zero. Infinitely large amount of work is required to maintain absolute zero if at all it can be achieved.

## COMPARISON BETWEEN GAS CYCLES AND VAPOR CYCLES

Thermodynamic cycles can be categorized into gas cycles and vapour cycles. In a typical gas cycle, the working fluid (a gas) does not undergo phase change, consequently the operating cycle will be away from the vapour dome.

In **Gas cycles**, heat rejection and refrigeration take place as the gas undergoes sensible cooling and heating. In a **Vapour cycle** the working fluid undergoes phase change and refrigeration effect is due to the vaporization of refrigerant liquid. If the refrigerant is a pure substance then its temperature remains constant during the phase change processes. However, if a zeotropic mixture is used as a refrigerant, then there will be a temperature glide during vaporization and condensation. Since the refrigeration effect is produced during phase change, large amount of heat (latent heat) can be transferred per kilogram of refrigerant at a near constant temperature.

Hence, the required mass flow rates for a given refrigeration capacity will be much smaller compared to a gas cycle. Vapour cycles can be subdivided into

- Vapour compression systems
- Vapour absorption systems
- Vapour jet systems etc.

Among these the vapour compression refrigeration systems are predominant.

## THE CARNOT REFRIGERATION CYCLE

Carnot refrigeration cycle is a completely reversible cycle, hence is used as a model of perfection for a refrigeration cycle operating between a constant temperature heat source and sink. It is used as reference against which the real cycles are compared.

The basic Carnot refrigeration system for pure vapour consists of four components: Compressor, Condenser, Turbine and Evaporator. Refrigeration effect ( $q_4 - q_1 = q_e$ ) is obtained at the evaporator as the refrigerant undergoes the process of vaporization (process 4-1) and extracts the latent heat from the low temperature heat source.

1. The low temperature, low pressure vapour is then compressed isentropically in the compressor to the heat sink temperature  $T_c$ . The refrigerant pressure increases from  $P_e$  to  $P_c$  during the compression process (process 1-2) and the exit vapour is saturated.
2. Next the high pressure, high temperature saturated refrigerant undergoes the process of condensation in the condenser (process 2-3) as it rejects the heat of condensation ( $q_{2-3} = q_c$ ) to an external heat sink at  $T_c$ .
3. The high pressure saturated liquid then flows through the turbine and undergoes isentropic expansion (process 3-4). During this process, the pressure and temperature fall from  $P_c, T_c$  to  $P_e, T_e$ . Since a saturated liquid is expanded in the turbine, some amount of liquid flashes into vapour and the exit condition lies in the two-phase region.
4. This low temperature and low pressure liquid-vapour mixture then enters the evaporator completing the cycle. the cycle involves two isothermal heat transfer processes (processes 4-1 and 2-3) and two isentropic work transfer processes (processes 1-2 and 3-4).
- 5.

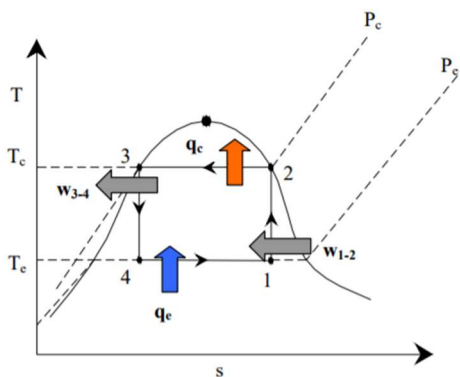
Heat is extracted isothermally at evaporator temperature  $T_e$  during process 4-1, heat is rejected isothermally at condenser temperature  $T_c$  during process 2-3. Work is supplied to the compressor during the isentropic compression (1-2) of refrigerant vapour from evaporator pressure  $P_e$  to condenser pressure  $P_c$ , and work is produced by the system as refrigerant liquid expands isentropically in the turbine from condenser pressure  $P_c$  to evaporator pressure  $P_e$ . All the processes are both internally as well as externally reversible, i.e., net entropy generation for the system and environment is zero. Applying first and second laws of thermodynamics to the Carnot refrigeration cycle,

$$\oint \delta q = \oint \delta w$$

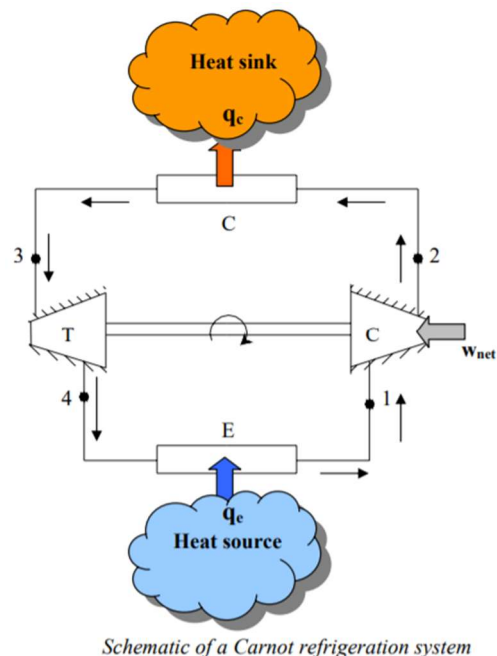
$$\oint \delta q = q_{4-1} - q_{2-3} = q_e - q_c$$

$$\oint \delta w = w_{3-4} - w_{1-2} = w_T - w_C = -w_{net}$$

$$\Rightarrow (q_c - q_e) = w_{net}$$



**Fig. 10.1(b):** Carnot refrigeration cycle on T-s diagram



*Schematic of a Carnot refrigeration system*



now for the reversible, isothermal heat transfer processes 2-3 and 4-1, we can write:

$$q_c = -q_{2-3} = -\int_2^3 T.ds = T_c(s_2 - s_3)$$

$$q_e = q_{4-1} = \int_4^1 T.ds = T_e(s_1 - s_4)$$

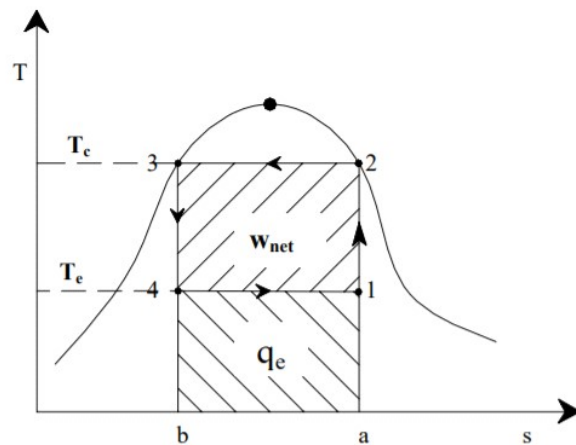
where  $T_e$  and  $T_c$  are the evaporator and condenser temperatures, respectively, and,

$$s_1 = s_2 \text{ and } s_3 = s_4$$

the Coefficient of Performance (COP) is given by:

$$\text{COP}_{\text{Carnot}} = \frac{\text{refrigeration effect}}{\text{net work input}} = \frac{q_e}{w_{\text{net}}} = \frac{T_e(s_1 - s_4)}{T_c(s_2 - s_3) - T_e(s_1 - s_4)} = \left( \frac{T_e}{T_c - T_e} \right)$$

Thus **the COP** of Carnot refrigeration cycle is a function of evaporator and condenser temperatures only and is independent of the nature of the working substance. This is the reason why exactly the same expression was obtained for air cycle refrigeration systems operating on Carnot cycle. The Carnot COP sets an upper limit for refrigeration systems operating between two constant temperature thermal reservoirs (heat source and sink). From Carnot's theorems, for the same heat source and sink temperatures, no irreversible cycle can have COP higher than that of Carnot COP.



*Carnot refrigeration cycle represented in T-s plane*

It can be seen from the above expression that the COP of a Carnot refrigeration system increases as the evaporator temperature increases and condenser temperature decreases. This can be explained very easily with the help of the T-s diagram



## ANALYSIS OF STANDARD VAPOUR COMPRESSION REFRIGERATION SYSTEM

A simple analysis of standard vapor compression refrigeration system can be carried out by assuming a) Steady flow; b) negligible kinetic and potential energy changes across each component, and c) no heat transfer in connecting pipe lines. The steady flow energy equation is applied to each of the four components.

Evaporator: Heat transfer rate at evaporator or *refrigeration capacity*,  $\dot{Q}_e$  is given by:

$$\dot{Q}_e = \dot{m}_r (h_1 - h_4)$$

where  $\dot{m}_r$  is the refrigerant mass flow rate in kg/s,  $h_1$  and  $h_4$  are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively.  $(h_1 - h_4)$  is known as specific refrigeration effect or simply *refrigeration effect*, which is equal to the heat transferred at the evaporator per kilogram of refrigerant. The evaporator pressure  $P_e$  is the saturation pressure corresponding to evaporator temperature  $T_e$ , i.e.,

$$P_e = P_{\text{sat}}(T_e)$$

Compressor: Power input to the compressor,  $\dot{W}_c$  is given by:

$$\dot{W}_c = \dot{m}_r (h_2 - h_1)$$

where  $h_2$  and  $h_1$  are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor, respectively.  $(h_2 - h_1)$  is known as specific work of compression or simply *work of compression*, which is equal to the work input to the compressor per kilogram of refrigerant.

Condenser: Heat transfer rate at condenser,  $\dot{Q}_c$  is given by:

$$\dot{Q}_c = \dot{m}_r (h_2 - h_3)$$

where  $h_3$  and  $h_2$  are the specific enthalpies (kJ/kg) at the exit and inlet to the condenser, respectively.

The condenser pressure  $P_c$  is the saturation pressure corresponding to evaporator temperature  $T_c$ , i.e.,

$$P_c = P_{\text{sat}}(T_c)$$

Expansion device: For the isenthalpic expansion process, the kinetic energy change across the expansion device could be considerable, however, if we take the control volume, well downstream of the expansion device, then the kinetic energy gets dissipated due to viscous effects, and

$$h_3 = h_4$$

The exit condition of the expansion device lies in the two-phase region, hence applying the definition of quality (or dryness fraction), we can write:

$$h_4 = (1 - x_4)h_{f,e} + x_4 h_{g,e} = h_f + x_4 h_{fg}$$

where  $x_4$  is the quality of refrigerant at point 4,  $h_{f,e}$ ,  $h_{g,e}$ ,  $h_{fg}$  are the saturated liquid enthalpy, saturated vapour enthalpy and latent heat of vaporization at evaporator pressure, respectively.

The COP of the system is given by:

$$\text{COP} = \left( \frac{\dot{Q}_e}{\dot{W}_c} \right) = \left( \frac{\dot{m}_r (h_1 - h_4)}{\dot{m}_r (h_2 - h_1)} \right) = \frac{(h_1 - h_4)}{(h_2 - h_1)} \quad (10.29)$$

At any point in the cycle, the mass flow rate of refrigerant  $\dot{m}_r$  can be written in terms of volumetric flow rate and specific volume at that point, i.e.,

$$\dot{m}_r = \frac{\dot{V}}{v}$$

applying this equation to the inlet condition of the compressor,

$$\dot{m}_r = \frac{\dot{V}_1}{v_1}$$

where  $\dot{V}_1$  is the volumetric flow rate at compressor inlet and  $v_1$  is the specific volume at compressor inlet. At a given compressor speed,  $\dot{V}_1$  is an indication of the size of the compressor. We can also write, the refrigeration capacity in terms of volumetric flow rate as:

$$\dot{Q}_e = \dot{m}_r (h_1 - h_4) = \dot{V}_1 \left( \frac{h_1 - h_4}{v_1} \right)$$

where  $\left( \frac{h_1 - h_4}{v_1} \right)$  is called as *volumetric refrigeration effect* (kJ/m<sup>3</sup> of refrigerant).

## IDEAL PROPERTIES FOR A REFRIGERANT

It will be useful to remind ourselves of the requirements for a fluid used as a refrigerant.

- A high latent heat of vaporization
- A high density of suction gas
- Non-corrosive, non-toxic and non-flammable
- Critical temperature and triple point outside the working range
- Compatibility with component materials and lubricating oil
- Reasonable working pressures (not too high, or below atmospheric pressure)
- High dielectric strength (for compressors with integral motors)
- Low cost
- Ease of leak detection
- Environmentally friendly

No single fluid has all these properties, and meets the new environmental requirements.

<i>Typical application</i>	<i>Refrigerants recommended</i>
Domestic refrigerators and freezers	R12
Small retail and supermarkets	R12, R22, R502
Air-conditioning	R11, R114, R12, R22
Industrial	R717, R22, R502, R13B1
Transport	R12, R502

## **OZONE DEPLETION POTENTIAL (ODP)**

The ozone layer in our upper atmosphere provides a filter for ultraviolet radiation, which can be harmful to our health. Research has found that the ozone layer is thinning, due to emissions into the atmosphere of chlorofluorocarbons (CFCs), halons and bromides. The Montreal Protocol in 1987 agreed that the production of these chemicals would be phased out by 1995 and alternative fluids were developed. From Table, R11, R12, R114 and R502 are all CFCs used as refrigerants, while R13B1 is a halon. They have all ceased production within those countries which are signatories to the Montreal Protocol. The situation is not so clear-cut, because there are countries like Russia, India, China etc. who are not signatories and who could still be producing these harmful chemicals.

It should be noted that prior to 1987, total CFC emissions were made up from aerosol sprays, solvents and foam insulation, and that refrigerant emissions were about 10% of the total. However, all the different users have replaced CFCs with alternatives. R22 is an HCFC and now regarded as a transitional refrigerant, in that it will be completely phased out of production by 2030, as agreed under the Montreal Protocol. A separate European Community decision has set the following dates

<b>1/1/2000</b>	<b>CFCs banned for servicing existing plants</b>
<b>1/1/2000</b>	<b>HCFCs banned for new systems with a shaft input power greater than 150 kW</b>
<b>1/1/2001</b>	<b>HCFCs banned in all new systems except heat pumps and reversible systems</b>
<b>1/1/2004</b>	<b>HCFCs banned for <i>all</i> systems</b>
<b>1/1/2008</b>	<b>Virgin HCFCs banned for plant servicing</b>

### Comparison of new refrigerants

<i>Refrigerant type/no.</i>	<i>Substitute for</i>	<i>ODP</i>	<i>GWP</i>	<i>Cond. temp. at 26 bar (°C)</i>	<i>Sat. temp. at 1 bar abs °C</i>
<b>HCFC (short term)</b>					
R22	R502, R12	0.05	1700	63	– 41
<b>HFCFC/HFC service-blends (transitional alternatives)</b>					
R401A	R12	0.03	1080	80	– 33
R401B	R12	0.035	1190	77	– 35
R409A	R12	0.05	1440	75	– 34
<b>HFC–Chlorine free (long-term alternative)</b>					
R134A	R12, R22	0	1300	80	– 26
<b>HFC–Chlorine free–blends–(long-term alternatives)</b>					
R404A	R502	0	3750	55	– 47
R407A	R502	0	1920	56	– 46
R407B	R502	0	2560	53	– 48
R407C	R22	0	1610	58	– 44
ISCEON 59	R22	0	2120	68	– 43
R410A	R22, R13B1	0	1890	43	– 51
R411B	R12, R22, R502	0.045	1602	65	– 42
<b>Halogen free (long-term alternatives)</b>					
R717 ammonia	R22, R502	0	0	60	– 33
R600a isobutane	R114	0	3	114	– 12
R290 propane	R12, R22, R502	0	3	70	– 42
R1270 propylene	R12, R22, R502	0	3	61	– 48

### GLOBAL WARMING POTENTIAL (GWP)

Global warming is the increasing of the world's temperatures, which results in melting of the polar ice caps and rising sea levels. It is caused by the release into the atmosphere of so-called 'greenhouse' gases, which form a blanket and reflect heat back to the earth's surface, or hold heat in the atmosphere.

The most infamous greenhouse gas is carbon dioxide (CO<sub>2</sub>), which once released remains in the atmosphere for 500 years, so there is a constant build-up as time progresses. The main cause of CO<sub>2</sub> emission is in the generation of electricity at power stations. Each kWh of electricity used in the UK produces about 0.53 kg of CO<sub>2</sub> and it is estimated that refrigeration compressors in the UK consume 12.5 billion kWh per year. Table below shows that the newly developed refrigerant gases also have a global warming potential if released into the atmosphere.

**For example**, R134a has a GWP of 1300, which means that the emission of 1 kg of R134a is equivalent to 1300 kg of CO<sub>2</sub>. The choice of refrigerant affects the GWP of the plant, but other factors also contribute to the overall GWP and this has been represented by the term total equivalent warming impact (TEWI). This term shows the overall impact on the global warming effect, and includes refrigerant leakage, refrigerant recovery losses and



energy consumption. It is a term which should be calculated for each refrigeration plant. Figures below show the equation used and an example for a medium temperature R134a plant.

### Environmental impact of some of the latest refrigerants

Refrigerant		ODP (R11 = 1.0)	GWP (CO <sub>2</sub> = 1.0)
R22	HCFC	0.05	1700
R134a	HFC	0	1300
R404a	HFC	0	3750
R407c	HFC	0	1610
R410a	HFC	0	1890
R411b	HCFC	0.045	1602
R717	ammonia	0	0
R290	propane	0	3
R600a	isobutane	0	3
R1270	propylene	0	3

**TEWI** = TOTAL EQUIVALENT WARMING IMPACT

$$TEWI = (GWP \times L \times n) + (GWP \times m [1 - \alpha_{\text{recovery}}]) + (n \times E_{\text{annual}} \times \beta)$$

← Leakage → ← Recovery losses → ← Energy consumption →

← direct global warming potential → ← indirect global warming potential →

GWP = Global warming potential [CO<sub>2</sub>-related]

L = Leakage rate per year [kg]

n = System operating time [Years]

m = Refrigerant charge [kg]

$\alpha_{\text{recovery}}$  = Recycling factor

$E_{\text{annual}}$  = Energy consumption per year [kWh]

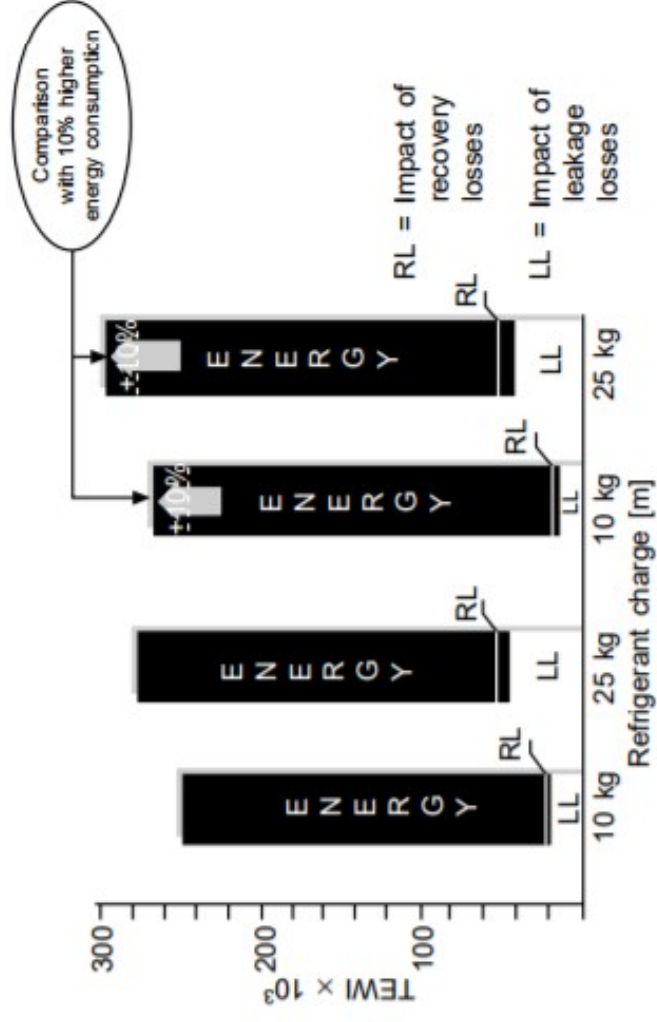
$\beta$  = CO<sub>2</sub>-Emission per kWh (Energy-Mix)

*Method for the calculation of TEWI figures*

### Example

Medium temperature R134a

$t_b$   $-10^{\circ}\text{C}$   
 $t_c$   $+40^{\circ}\text{C}$   
 $m$  10 kg // 25 kg  
 $L_{10\%}$  1 kg // 2,5 kg  
 $Q_0$  13,5 kW  
 $E$  5 kW  $\times$  5000 h/a  
 $\beta$  0,6 kg  $\text{CO}_2/\text{kWh}$   
 $\alpha$  0,75  
 $n$  15 years  
 GWP 1300 ( $\text{CO}_2 = 1$ ) time horizon 100 years



Comparison of TEWI figures (example)

One thing that is certain is that the largest element of the TEWI is energy consumption, which contributes CO<sub>2</sub> emission to the atmosphere. The choice of refrigerant is therefore about the efficiency of the refrigerant and the efficiency of the refrigeration system. The less the amount of energy needed to produce each kW of cooling, the less will be the effect on global warming

## **AMMONIA AND THE HYDROCARBONS**

These fluids have virtually zero ODP and zero GWP when released into the atmosphere and therefore present a very friendly environmental picture.

**Ammonia** has long been used as a refrigerant for industrial applications. The engineering and servicing requirements are well established to deal with its high toxicity and flammability. There have been developments to produce packaged liquid chillers with ammonia as the refrigerant for use in air-conditioning in supermarkets, for example. Ammonia cannot be used with copper or copper alloys, so refrigerant piping and components have to be steel or aluminum. This may present difficulties for the air conditioning market where copper has been the base material for piping and plant. One property that is unique to ammonia compared to all other refrigerants is that it is less dense than air, so a leakage of ammonia results in it rising above the plant room and into the atmosphere. If the plant room is outside or on the roof of a building, the escaping ammonia will drift away from the refrigeration plant. The safety aspects of ammonia plants are well documented and there is reason to expect an increase in the use of ammonia as a refrigerant.

**Hydrocarbons** such as propane and butane are being successfully used as replacement and new refrigerants for R12 systems. They obviously have flammable characteristics which have to be taken into account by health and safety requirements. However, there is a market for their use in sealed refrigerant systems such as domestic refrigeration and unitary air-conditioners.

## **REFRIGERANT BLENDS**

Many of the new, alternative refrigerants are '**Blends**', which have two or three components, developed for existing and new plants as comparable alternatives to the refrigerants being replaced. They are 'zeotropes' with varying evaporating or condensing temperatures in the latent heat of vaporization phase, referred to as the '**Temperature glide**'.



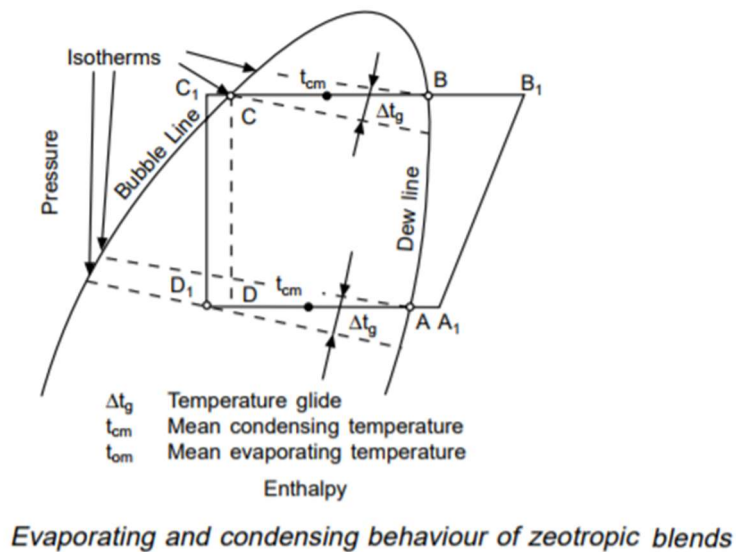


Figure above shows the variation in evaporating and condensing temperatures. To compare the performance between single component refrigerants and blends it will be necessary to specify the evaporating temperature of the blend to point A on the diagram and the condensing temperature to point B. The temperature glide can be used to advantage in improving plant performance, by correct design of the heat exchangers. A problem associated with blends is that refrigerant leakage results in a change in the component concentration of the refrigerant. However, tests indicate that small changes in concentration (say less than 10%) have a negligible effect on plant performance. The following recommendations apply to the use of blends:

- The plant must always be charged with liquid refrigerant, or the component concentrations will shift.
- Since most blends contain at least one flammable component, the entry of air into the system must be avoided.
- Blends which have a large temperature glide, greater than 5K, should not be used for flooded-type evaporators.

## HEALTH AND SAFETY

When dealing with any refrigerant, personal safety and the safety of others are vitally important. Service and maintenance staff need to be familiar with safety procedures and what to do in the event of an emergency. Health and safety requirements are available from manufacturers of all refrigerants and should be obtained and studied. Safety codes are available from the Institute of Refrigeration in London, for HCFC/HFC refrigerants (A1 and A2), ammonia (B2) and hydrocarbons (A3). In the UK and most of Europe, it is illegal to dispose of refrigerant in any other way than through an authorized waste disposal company. The UK legislation expects that anyone handling refrigerants is competent to do so and has the correct equipment and containers. Disposal must be through an approved contractor and must be fully documented. Severe penalties may be imposed for failure to implement these laws