CHAPTER 3

THERMODYNAMIC ANALYSIS

It is customary practice to deal the basic principles involved in any thermal system by applying principles of thermodynamics. In general a refrigeration system requires an external power to normalise the hot surrounding either for human comfort or a cooling process. For example; it is evident that the operation of vapour compression refrigeration system involves compressor work and is essential to achieve refrigeration. An adsorption refrigeration system also operates like a vapour compression system except that the compressor is replaced by sorption bed and is known as thermal compressor. Unlike vapour compression system that is actuated with high grade energy, the adsorption refrigeration can be operated with low-grade energy (i.e. solar). This chapter pertains to thermodynamic cycle analysis of solar adsorption refrigeration system, working principle, governing equations and bed parameters.

3.1 DESCRIPTION OF THE SYSTEM

A schematic diagram of the solar vapour adsorption refrigeration system is depicted in figure 3.1. The system comprises of sorption bed, condenser, liquid storage tank, expansion device and evaporator. The adsorbent in powder form is packed in the sorption bed. Refrigerant vapour from evaporator is adsorbed by adsorbent during sun-off period. This vapour is desorbed due to heat received from
Figure 3.1 Schematic diagram of adsorption refrigeration system

Figure 3.2 Thermodynamic cycle of adsorption refrigeration system
sun during day cycle. The desorbed vapour entering the condenser is converted to liquid. The liquid refrigerant does return to evaporator after passing over an expansion device.

Figure 3.2 describes the thermodynamic processes involved in the operation of the adsorption refrigeration system. Isosteric (constant mass concentration ratio) pressurisation process (a-b) of vapour occurs initially on sorption bed heating. It makes the vapour pressure increase from the evaporation pressure to the condensation pressure. Subsequent addition of heat leads to desorption process (b-c) and followed by condensation. The liquid refrigerant flows to evaporator on isosteric depressurisation process (c-d). As the adsorber releases heat, cooling takes place. Consequently, the adsorbent temperature falls down, the vapour pressure is dropped down to the evaporation pressure. Thus, on receipt of latent heat from the space of cooling, the refrigerant is evaporated and subsequently adsorbed by the solid sorbent in the adsorber. The most common refrigeration cycle on p-h plot is given in figure 3.3 analogues to figure 3.2 of VA_4RS.

![Figure 3.3 Thermodynamic cycle of vapour refrigeration system](image)
3.2 FUNCTIONS OF ADSORBENT AND ADSORBATE

The adsorption refrigeration cycle depends on the adsorption of a refrigerant vapour by the solid sorbent at low pressure and temperature (evaporator side) and consequent desorption by heating at high pressure and temperature (condenser side). Satisfactory performance of adsorption refrigeration relies on working pairs chosen on the basis of application, heat source and refrigeration required locality. Therefore, it is essential to meet the required cooling demand by right selection of adsorbent-adsorbate pair (eg; AC-methanol, zeolite-water and so on).

3.3 ANALYSIS OF ADSORPTION SYSTEMS

It is common practice to evaluate any thermal system with use of different operating conditions and is rarely done by most of the investigators. The analysis of a vapour adsorption system includes the optimisation of the operating parameters in order to obtain maximum coefficient of performance. The first step involves the adsorbate mass flow rate calculation. The adsorbate mass flow rate can be calculated by using the capability of the refrigeration system and the cooling obtained in the system.

3.4 GOVERNING EQUATIONS

The complete operation of vapour adsorption refrigeration system rests on two vital processes, namely; i) heating process (desorption) and ii) cooling process (adsorption) as discussed in Section 3.1. Heat supplied in the form of solar energy to sorption bed contributes initially in sensible heating of adsorbent at the same time desorption of vapour seldom occurs. However, this sensible heating helps in isosteric pressurisation from evaporator pressure to condenser pressure. On reaching condensation pressure, refrigerant vapour starts dissociating from adsorbent due to
further heating. Therefore, concentration of refrigerant vapour increases from minimum to a maximum value during desorption process. The value of concentration expressed in terms of temperature of the bed using D-A equation (Critoph, 1996) as,

\[
M_x = M_0 \exp \left[ -k' \left( \frac{T}{T_{sat}} - 1 \right)^n \right]
\]  

(3.1)

where, the exponent \( n' \) describes the surface heterogeneity and \( k' \) relates to affinity coefficient.

The heat associated with sensible heating during the process a-b is expressed as,

\[
Q_{ab} = \int_{T_a}^{T_b} \left( C_{p,ad} + M_{\max} C_{p,ref} \right) dT
\]  

(3.2)

The heat associated with desorption of refrigerant from adsorbent during the process b-c, is expressed as,

\[
Q_{bc} = \int_{T_b}^{T_c} \left( C_{p,ad} + M_x C_{p,ref} \right) dT + \int_{M_{\max}}^{M_{\min}} H_a dM
\]  

(3.3)

In the above expression, the heat corresponding to phase heating of desorbing refrigerant is approximated as,

\[
H = R \left( C_{p,ad} + M_x C_{p,ref} \right) \left( \frac{T}{T_{sat}} \right)
\]  

(3.4)

Total heat required for heating the adsorbent bed is estimated as,

\[
Q_{gen} = Q_{ab} + Q_{bc}
\]  

(3.5)

Further, \( M_{\max} \) and \( M_{\min} \) can also be computed using eq. (3.1) corresponding to adsorption and desorption temperatures.

The net cooling capacity of evaporator is expressed as,

\[
Q_{ref} = m_{ref} \left( M_{\max} - M_{\min} \right) \left( h_{evap} - h_{cond} \right)
\]  

(3.6)

The above equations are used to obtain the required parameters in analysis of VA\(_d\)RS.
3.5 **VAₐRS PERFORMANCE ANALYSIS**

The coefficient of performance of single adsorbent bed can be estimated as the ratio of total refrigeration capacity of the system to the total heat supplied to the system. For theoretical analysis, the system performance is compared by two parameters, namely, Carnot COP and theoretical COP.

The Carnot COP can be expressed as,

$$COP_{carnot} = \left( \frac{T_{\text{gen}} - T_{\text{cond}}}{T_{\text{gen}}} \right) \left( \frac{T_{\text{evap}}}{T_{\text{ads}} - T_{\text{evap}}} \right)$$

(3.7)

The theoretical COP is expressed as,

$$COP = \frac{Q_{\text{evap}}}{Q_{ab} + Q_{bc}}$$

(3.8)

The eq. (3.8) can be re-written as,

$$COP = \frac{Q_{\text{evap}}}{Q_{\text{gen}}}$$

(3.9)

The specific cooling power is expressed as,

$$SCP = \frac{Q_{\text{evap}}}{m_{ad}}$$

(3.10)

3.6 **PERFORMANCE PREDICTION**

The matlab code used to predict the performance of the vapour solid sorption refrigeration system. The code includes all governing equations described above. Thermodynamic properties of refrigerants are found using data available in literature Claus Borgnakke and Sonntag, (1997). The model also includes operating parameters, $T_{\text{evap}}$, $T_{\text{des}}$, $T_{\text{cond}}$, $T_{\text{ads}}$, $M_{\text{min}}$, and $M_{\text{max}}$ along with pressure at evaporator, condenser, sorption bed during adsorption and desorption as the input for computing COP, Carnot COP, SCP, $Q_{\text{evap}}$ and $Q_{\text{gen}}$. Figure 3.4 describes the algorithm involved in computation of outputs. MATLAB simulation code is given in Appendix A.
3.7 CONCLUDING REMARKS

The environmental-friendly refrigerants such as methanol and water are chosen for the comparative study. The pattern of variation of COP, Carnot COP and SCP are studied for designated refrigerants. However these parameters are found to be different for different refrigerants at the same operating environments. Among the working fluids selected, methanol gives a better performance and higher COP values at low working temperatures and water gives higher specific cooling power under same operating conditions as in methanol.