COMPARATIVE ANALYSIS OF SINGLE AND TWO STAGE ACTIVATED CARBON+HFC134A REFRIGERATION SYSTEMS

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Abstract

This paper focuses on the analysis of comparative performance of single and two stage adsorption refrigeration systems (HFC-134a + Activated carbon). To achieve design throughput from the thermal compressor, they have to be designed to contained adequate amount of the adsorbent. A criterion which takes into account on the void volume and finite time of reaching equilibrium adsorption conditions is proposed. The void volume effect is taken into account by defining an uptake efficiency of the compressor. The overall refrigeration system performance is evaluated through two features, namely, the coefficient of performance (COP) and the exergetic efficiency. These have been calculated for single and two stage systems for various evaporating, condensing and desorbing conditions. The other variants are packing density of the activated carbon and various specimens. Through these data the suitability of single or two stage systems for a specific application is established.

Key words: Activated carbon; refrigeration; single and two stage systems; exergetic efficiency.

1. Introduction

There is a global thrust towards the minimum usage of conventional energy based on fossil fuels and maximum recovery of waste heat. On the other hand, refrigeration contributes to significant levels of primary energy usage. In this context, adsorption refrigeration systems can be construed to be viable alternatives to existing practices. They can be operated with waste heat, which is essentially a low grade thermal energy. Added advantages are absence of moving parts, vibrations and lubrication requirements. Adsorption system is also scalable to any range of refrigeration load from a few watts to several kilowatts. In particular, in the area of cooling of electronics, where electromagnetic interference effects have to be considered, adsorption cooling systems could have an edge over other active cooling methods such as thermoelectric refrigeration. Yet, they also possess some disadvantages such as large thermal mass, bulkiness and complex controls for sequential operation of multiple compressors. This paper is a sequel to our recent efforts [1-3] on the understanding of the intricate relationship between the properties of the adsorbent and adsorbate on the throughput of the compressor and its overall contribution to the system performance. The motivating factor is to reduce the effects of void volume through multistage thermal compression. For cryo-adsorption systems Bard [4] has shown that it would be beneficial. However, such processes for refrigeration systems have been seldom explored.

This paper mainly focuses on a comparative study of two and single stage adsorption systems. Activated carbon is taken as the adsorbent and HFC-134a as the adsorbate. A new performance indicator, namely, uptake efficiency is defined which has a bearing on the sizing multiplication factor. The latter determines the size of the thermal compressor. The outcome of the analysis is the identification of the conditions under which a two stage system gives a better performance than a single stage one. The other influencing factors are (a) combinations of adsorption/ desorption temperatures, evaporating temperatures and condensing temperatures, (b) packing density of the adsorbent and (c) types of activated carbon.

2. Compression in adsorption refrigeration system

Except the compression process, in adsorption compressor, all other processes are the same as in a vapor compression system. Compression in the single stage adsorption compressor consists of four processes, namely, adsorption and cooling, heating and pressurization, desorption and heating and cooling and depressurization. The p-c-T planes of these processes are shown in figures 1 and 2 for single and two stage systems, respectively.

In the two stage thermal compression system, enhancement of density is achieved in two stages. In the first stage the refrigerant is compressed up to an intermediate pressure p_I, which is the square root product of condensing pressure p_{con} and evaporating pressure p_e. By passing through the intercooler, the adsorbate is cooled from desorption temperature (T_{des}) to adsorption temperature (T_{ad}) and then enters in the second compressor (Figure 2). The objective is to obtain as large an uptake difference as possible across each stage of compression (C_b-C_d and C_f-C_e).

3. Void volume

To achieve a significant adsorptive capacity, an adsorbent must have a high surface area, which implies a highly porous structure with a large micropore volume. The adsorptive properties depend upon the pore size and its distribution.

The void volume is created by interparticle gap, the macropores and to some extent, the mesopores. In the first instance the refrigerant already present in the void volume of the thermal compressor gets adsorbed. This reduces the ability of filling of micropores by the adsorbate coming from the evaporator. Thus, although C_b-C_a is the uptake difference across which thermal compressor is ideally expected to operate, the actual operation is less by a-a' (Figure 1).

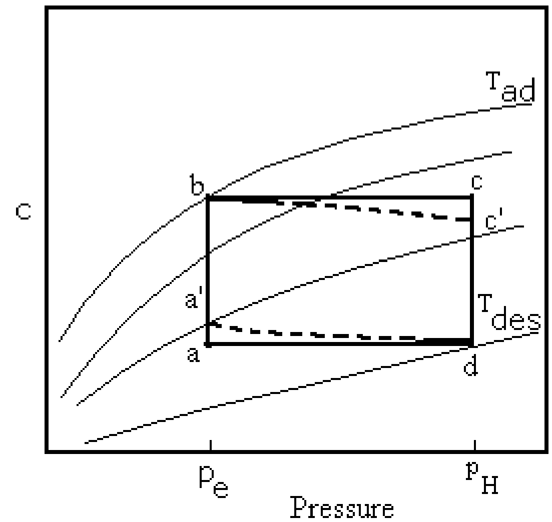


Figure 1a. Compressor cycle in VAd system
a-b: Cooling and adsorption
b-c: Heating and pressurisation
c-d: Heating and desorption
d-a: Cooling and depressurisation
a-a': adsorption loss due to void volume
c-c': desorption loss due to void volume

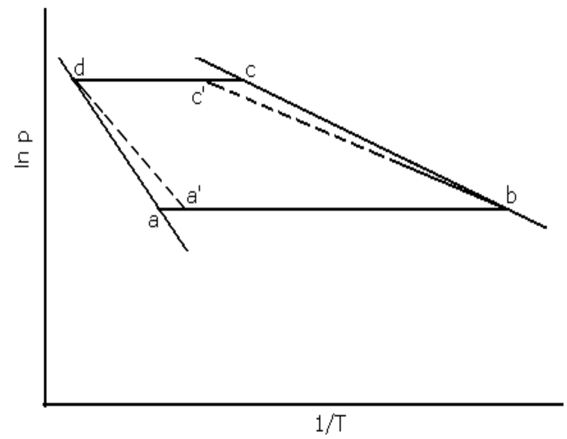
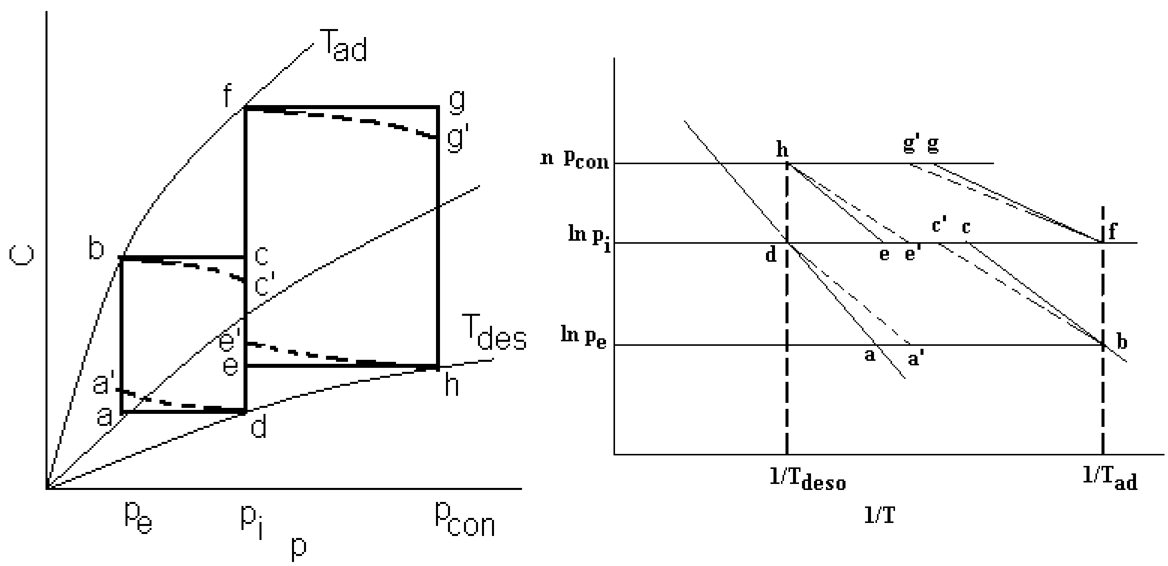


Figure 1b. Compressor cycle on ln p vs 1/T plane



(a) (b)

Figure 2. Two stage cooler on p-c-T plane. Ideal cycles: a-b-c-d - Low stage; e-f-g-h- high stage. Real cycles: a'-b-c'-d - Low stage; e'-f-g'-h - high stage.

In a similar way, during desorption (c-d in Figure. 1), the adsorbate released from the micropores in the first instance, increases the pressure in the void volume. Certain amount of the adsorbate does not contribute to the throughput of the compressor. Thus, the void volume in an adsorption compressor behaves identically like the clearance volume in a reciprocating compressor.

We define the thermal compression uptake efficiency (analogous to volumetric efficiency of a positive displacement compressor) as

$$\eta_u = \Delta c'/\Delta c = (c_b - c_{a'})/(c_b - c_a) \qquad (1)$$

which has been shown [3] to be equivalent to

$$\eta_u = 1 + (\Delta\rho/\Delta c)[(1/\rho_{eff}) - (1/\rho_s)] \qquad (2)$$

where ΔC is the difference in the density of the adsorbate between the thermodynamic states at b and d (Figure. 1).

$$\Delta\rho = \rho_b - \rho_d \qquad (3)$$

which is invariably negative due to the fact that the specific volume of the refrigerant decreases due to compression i.e. $\rho_b < \rho_d$. Consequently, the uptake efficiency will be always <1. $\Delta\rho$ is the thermodynamic property of the adsorbate. ΔC is a combined property of the adsorbent and adsorbate while ρ_{eff} is a mechanical property of the adsorbent. Realization of large uptake efficiencies will be possible when ΔC is large i.e. the compressor operates across small pressure differentials (Figure. 1) or when high ρ_{eff} can be achieved. The latter is limited by the compacting ability of powder/ granular form of activated carbon, in our case, seldom $\rho_{eff} > 1000$ kg/m^3 could be achieved.

4. Multification factor

The sizing of each of the thermal compressors is done as follows. The mass flow rate of refrigerant $(\dot{m}_r)$ to meet the cooling demands is arrived at from the cooling load and the enthalpy change of the refrigerant in the evaporator for a given set of condensing and evaporating temperatures. The minimum amount of refrigerant that needs to be adsorbed is the product of this flow rate and the time of adsorption (t_{ad})

$$m_{ad} = (\dot{m}_r)\, t_{ad} \qquad (4)$$

The minimum amount of activated carbon required per compressor to adsorb this quantity of refrigerant is set as

$$m_{ch} = \frac{m_{ad}}{C_b - C_d} \tag{5}$$

Subscripts b and d refers to the states shown in Figure 1. However, the actual amount of activated carbon required will be governed by (c_b-$c_{a'}$) such that

$$m_{ch} = \frac{m_{ad}}{(C_b - C_d)\eta_u} \tag{6}$$

Eq. (6) assumes equilibrium conditions which again are not possible in practice because the cycle time has to be restricted. A large cycle time will indent a large number of compressors and a short cycle time would cause a loss of throughput. In general, the throughput of the compressor is quite small after one time constant of the desorption [5]. Thus, a sacrifice of 37 % of the throughput seems to be inevitable to limit the cycle times to about a few 100’s of seconds.

In general, if the desorption is allowed for ‘n’ time constants (τ), the loss due to non-equilibrium conditions would be ($1\text{-}e^{-n\tau}$). This is equivalent to further loss of volumetric efficiency. Hence the mass of charcoal required will be

$$m_{ch} = \frac{m_{ref}\ t_{ad}}{(C_b - C_d)}\left[\frac{1}{\eta_u - (1 - e^{-n\tau})}\right] \tag{7}$$

We define a multiplication factor for the amount of charcoal as

$$MF = \frac{1}{\eta_u - (1 - e^{-n\tau})} \tag{8}$$

This factor is similar to the ‘α’ factor proposed by Burger et al. [6] for activated carbon-nitrogen systems.

5. Results and discussion

The adsorption data for various specimens given by Akkimaradi et al. [7] were used to calculate C_b-C_d in above equations.

5.1 Uptake efficiencies

In figure 3 uptake efficiencies are compared for single and two stage adsorption compressors. In a two stage system, for the first compressor as well as the second compressor, the uptake efficiency is nearly 1. This augmentation is because of a large ΔC being available due to small pressure differentials across which it opereates. At lower evaporating temperatures, for single stage system, the ΔC is small which reduces the uptake efficiency and vice-versa at higher evaporating temperatures.

When different specimens of activated carbon are considered (Figure 4), it is seen that Maxsorb has the highest uptake efficiency, followed by Fluka and Chemviron (Figure 4). ΔC is purely governed by adsorption characteristics of the adsorbent-adsorbate pair for a given set of operating conditions. If we allow only one time constant for adsorption and desorption, 37 % of the available throughput is lost. Therefore, if it is compelled that at least require 40 % of the throughput should be acquired, the minimum uptake efficiency of 77 % will be required. It can be seen from the figure 3 that for conditions T_{ad} = 40 ^oC, T_{des} = 100 ^oC and ρ_{eff} = 280 kg/m^3 a two stage system will satisfy the criterion for all the evaporating conditions. On the other hand, below 1 ^oC a single stage system will not meet the requirement. Figure 4 shows that this criterion is not satisfied by Chemviron and Fluka for the specified range of conditions.

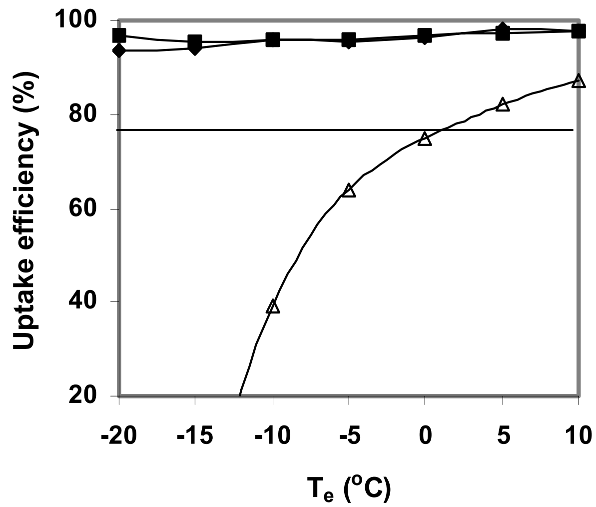


Figure 3. Comparison of uptake efficiencies of single stage . □ and two stage (◊-low stage; □- high stage) at various evaporating conditions; Specimen- Maxsorb, T_{ad} = 40 ^oC, T_{des} = 100 ^oC,ρ_{eff} = 280 kg/m^3,
Open symbol: single stage
Filled symbol: two stage

For large differences of (T_{des}-T_{ad}), the uptake efficiency can become negative. The limiting ΔC where this happens can be found from eq (2) as

$$\Delta C = \frac{|\Delta \rho|}{\left[\dfrac{1}{\rho_{eff}} - \dfrac{1}{\rho_s}\right]} \tag{9}$$

This happens in the case of Maxsorb for ρ_{eff} = 280 kg/m^3 and T_{ad} = 40 ^oC, T_{des} = 100 ^oC and T_e < -15 ^oC. To extend the lower limit of evaporating temperatures one needs to increase ρ_{eff}. Its effect is depicted in Figure 5. The choices available to the designer are i) to increase ρ_{eff} or ii) to adopt a two stage system. The former is quite difficult to achieve with powder and granular activated carbons.

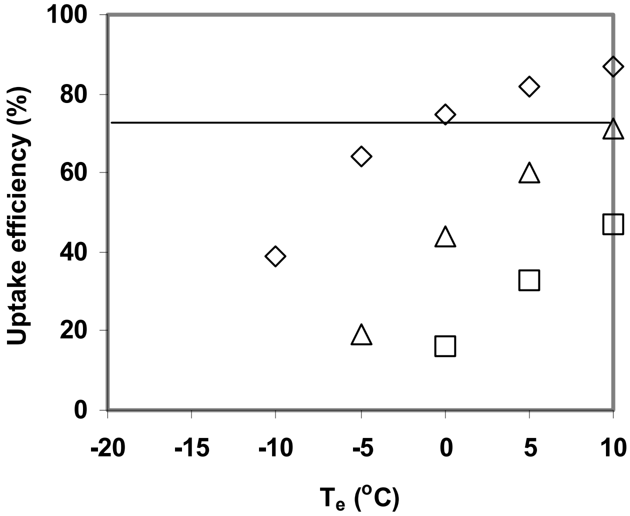


Figure 4. Comparison of uptake efficiencies for Maxsorb (◇), Fluka (Δ),Chemviron (□) in single-stage for T_{ad} = 40 °C, T_{des} = 100 °C, ρ_{eff} = 280 kg/m^3

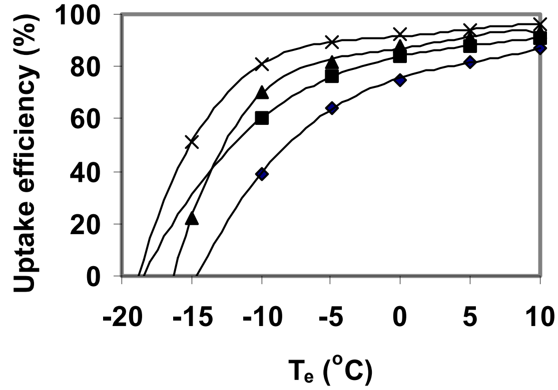


Figure 5. Variation of uptake efficiencies with packing densities, ρ_{eff} = 280 kg/m^3 (◆), ρ_{eff} = 400 kg/m^3 (■), ρ_{eff} = 500 kg/m^3 (▲) and ρ_{eff} = 600 kg/m^3 (×) in single stage. T_{ad} = 40 °C, T_{des} = 100 °C

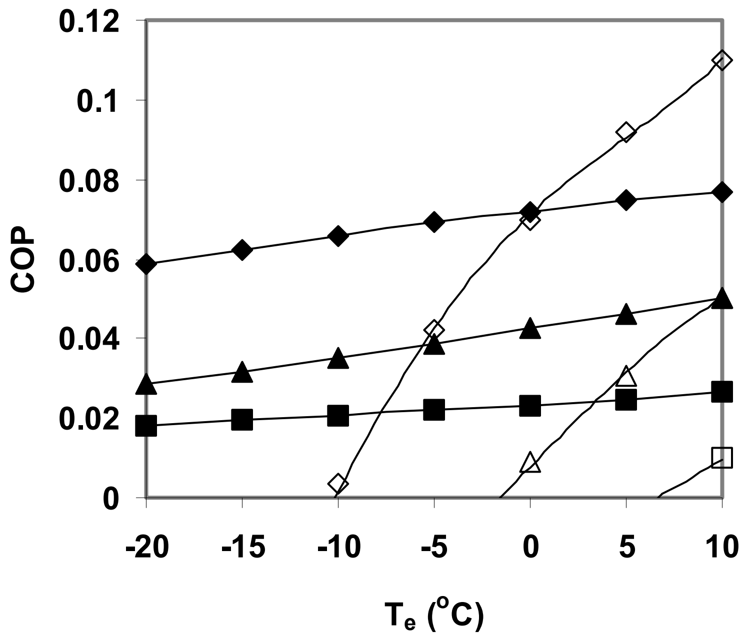


Figure 6. Comparison of COP for single and two-stage for T_{ad} = 40 °C, T_{des} = 100 °C with Maxsorb (ρ_{eff} = 280 kg/m^3), Fluka (ρ_{eff} = 462 kg/m^3), Chemviron (ρ_{eff} = 484 kg/m^3) ;
Legend: Maxsorb (◇); Fluka (Δ); Chemviron (□),
Open symbol: single stage
Filled symbol: two stage

5.2 COP and Exergetic efficiency

The COP is calculated per cycle in the conventional way as the ratio between the cooling capacity to thermal energy needs. The exergetic efficiency is the ratio of actual COP to Carnot COP given by

$$\text{Exergetic efficiency} = \frac{\text{COP}}{\text{Carnot COP}} \times 100 \tag{10}$$

where,

$$\text{Carnot COP} = \left(\frac{T_{des} - T_{ad}}{T_{des}}\right)\left(\frac{T_e}{T_{ad} - T_e}\right) \tag{11}$$

These two are salient indicators of the performance of refrigeration systems. While a two stage system could appear promising from uptake efficiency point of view, it warrants doubling of number of compressors and consequent complications in logistics of operation. Figure 6 gives a plot of these two parameters for single and two stage systems.

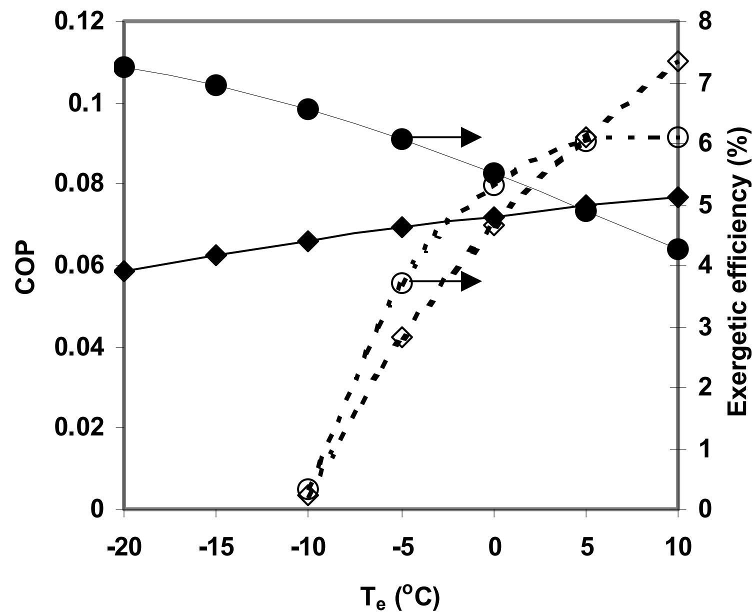


Figure 7. Comparison of COP and Exergetic efficiency for single and two-stage; T_{ad} = 40 ^{o}C, T_{des} = 100 ^{o}C

Legend: COP (◇), Exergetic efficiency (○)
Specimen: Maxsorb; Open symbol: single stage
Filled symbol: two stage

Two important observations can be made: i) The COP of a two stage system remains fairly uniform over the entire range of evaporating temperatures, and ii) single stage system is beneficial in the case of Maxsorb specimen above $T_e \cong 0$ ^{o}C. But, the dependence of COP on T_e is quite strong. In the case of the other two specimens the two stage systems yield a better COP than single stage units.

Figure. 7 shows the variation of exergetic efficiency and COP for Maxsrob for conditions as in Fig. 6. The former is equal to or better for a single stage system for $T_e \geq 0$ °C. Yet, a two stage system gives a fairly uniform performance over a wide range of evaporating temperatures.

5.3 Operating conditions

The previous section focused on comparison of different specimens of adsorbent under various evaporating temperatures, but a fixed adsorption and desorption temperatures. In practice, the adsorption temperatures also could vary depending on ambient conditions. Hence, a comparison of single and two stage systems for these conditions is also appropriate. Figure 8 shows these effects. As the adsorption temperature increases the COP declines because of decrease in ΔC. Further, at lower adsorption temperatures single stage is advantageous. But, as temperature increases two stage becomes better. Both these effects are about the same as in conventional vapor compression refrigeration systems.

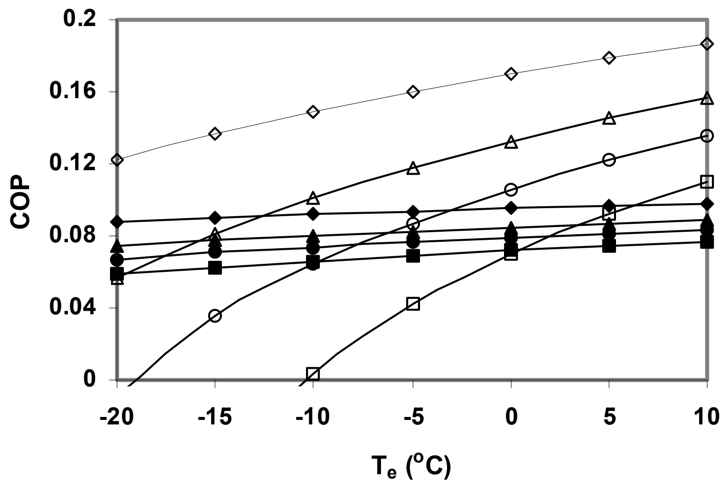


Figure 8. Variation COP at various adsorption temperatures; Specimen: Maxsorb, ρ_{eff} = 280 kg/m^3, T_{des} = 100 °C.
Legend: T_{ad} = 20 °C (◇); T_{ad} = 30 °C (Δ); T_{ad} = 35 °C (○); T_{ad} = 40 °C (□);
Open symbol: single stage; Filled symbol: two stage

6. Conclusion

This paper elucidates selection criterion for single and two stage thermal compression in an adsorption refrigeration cycle using activated carbon as the adsorbent and HFC-134a as the refrigerant. The governing features are the uptake efficiency, the COP and the exergetic efficiency. It is concluded that a two stage system has the flexibility for the operation in a large domain of operating conditions, *albeit*, with double the number of compressors and associated operating complexities. Yet, for typical applications involving cooling of electronic equipment, a single stage unit could be quite adequate.

Acknowledgements

The first author is thankful to All India Council of Technical Education for providing National Doctoral Fellowship. The work reported in this paper was supported by a research grant form the Defence Research and Development Organisation, Government of India.

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