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Experimental Analysis of Mechanical and Adsorption Hybrid Refrigeration with CO_2 as Refrigerant and Activated Carbon as Absorbent

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Abstract— **The refrigeration industry is constantly looking for new techniques and refrigerants in order to deal with the ever growing concern over global warming and ozone layer depletion. Regarding this, many novel ideas have been tested. But still, vapor compression refrigeration (VCR) remains the preferred option and any effort to decrease the energy consumption in VCR and also simultaneously addressing the issue of global warming will be a progressive step.**

This paper presents the results of an investigation on the suitability of hybrid compression process for refrigerant CO_2 in cooling applications. CO_2 is one of the few natural refrigerants, which is neither flammable nor toxic. It is inexpensive, widely accessible and does not affect the global environment as do many other refrigerants. Although, it has high global warming potential but effectively that reduces to zero since it can be utilized from the industrial waste production. Moreover, in the present experiment, the conventional mechanical compression is supplemented by thermal compression using a series of adsorption compressors. Activated carbon is the adsorbent for the thermal compression segment as CO_2 is adsorbed very well by it. The alternatives of bottoming either mechanical or thermal compression stages are investigated. The outcome demonstrated that almost 23% energy can be conserved by fragmenting a part of the compression in a thermal compressor compared to the case when the entire compression is carried out in a single-stage mechanical compressor. The hybrid compression is feasible even when low grade heat is available. Some performance indicators are defined and evaluated for various configurations.

Keywords— Hybrid refrigeration, VCR, Thermal Compression

I. Introduction

The refrigeration and air conditioning consume about 10 to 15% of the available electric energy. The depletion of fossil fuel resources and the various protocols for the protection of the environment have catalyzed the process of development of cooling systems enabling the use of waste heat of industrial processes or a free energy source, such as solar energy and to propose solutions to augment the energy efficiency of conventional vapor compression systems.

The vapor compression refrigeration (VCR) with the positive displacement compressors (such as reciprocating, rotary, scroll or screw compressors) continues to be the mainstay of refrigeration demands. Thermoelectric, Liquid absorption, solid adsorption and thermo-acoustic cycles offer limited other options. Among them, vapor absorption has been the most popular. But still, scalability to low cooling capacity is not achieved and the choice of working pairs plays a crucial role. The most investigated and experimented combination is lithium bromide and water system, which cannot be used below about 5 deg C ,operation at sub-atmospheric pressures is an impediment. Further, it cannot be used in a hybrid compression system with conventional compression of water vapour. The other such widely investigated pair, ammonia and water, has the problem of infiltration of water vapour into the refrigeration circuit, need for high pressures and risks of ammonia in small scale refrigeration units.

In principle, solid adsorption based refrigeration systems have the advantage of scalability to all capacities, ranging from a few watts to several kilowatts [1]. A large amount of studies and experiments on solid sorption systems has been done in the last couple of decades. The adsorbents most investigated are zeolite (e.g. [2,3,4]), silica gel [5,6,7,8]) and activated carbons [9,10,11,12] while water, ammonia, methanol and ethanol are proposed as refrigerants.

The conflict is whether to continue with hydrofluorocarbon (HFC) refrigerants or if focus should be on natural refrigerants, such as ammonia and carbon dioxide or even flammable hydrocarbons is gaining prominence. With the advent of such highly regenerative cycles, such as multiple-beds [13], thermal waves [14] and the convective thermal wave [15], it may be worth considering high pressure refrigerants other than ammonia which have advantages such as compatibility with copper, or more convenient working pressure and so on.

As it is known, CO_2 is one of the few natural refrigerants, which is neither flammable nor toxic. CO_2 has a GWP = 1 (global warming potential, the GWP of HFC is 1000–3000), but the net global warming impact when used as a technical gas is zero, since the gas is a waste product from industrial production. It is cheap, easily available and is less harmful to the environment than other refrigerants. Therefore, CO_2 establishes itself as an excellent alternative among the natural refrigerants, particularly in applications where the toxicity and flammability of ammonia and hydrocarbons may be a problem. The promising applications of CO_2 refrigeration systems include automotive air conditioning, heat pumps, residential/commercial air conditioning and various refrigeration areas [16,17]. However, there has not been a considerable amount of work on adsorption refrigeration systems using CO_2 as the refrigerant.

The possibility of augmenting the energy requirements of conventional mechanical compression with adsorption based thermal compression deserves investigation. Moreover, a thermal compressor has virtually no moving parts and can be operated with heat sources close to the ambient [18]. The adsorption option negates the need for solution heat exchangers and pumps. One should also note that adsorption systems have their own set of disadvantages. For silica gel, they need frequent replacement and in the case of activated carbons, system practices of handling extremely fine microporous particles have to be developed further. Moreover, there should be significant variation of the adsorbents used for coolers from those used for other processes such as gas separation and purification.

Adsorption systems as sole systems have the disadvantage of operational complexities either with single-stage or two-stage compression [19,20]. When waste heat or low grade energy is easily available as in process industry or solar energy, such a combination of compression processes could be even more advantageous. This paper presents the results of an analysis of a hybrid compression system where the Primary focus to raise the pressure will be on mechanical compression and thermal compression will be the supplementing part. Thus, the focus is on energy conservation. Later, a comparison is made with single-stage mechanical and thermal compression and two-stage thermal compression. The position of thermal compression as low stage or high stage means is also investigated.

II. DESCRIPTION OF COMPRESSION PROCESS

Fig. 1 shows a schematic diagram of the hybrid cycle where the the low stage compression is given by adsorption process. T–s and p–h diagrams for the same are shown in Fig. 2. The refrigerant from evaporator goes to the adsorption compressor, where activated carbon absorbs it at near condensation temperature. It is then desorbed by supplying heat (at d). The refrigerant vapour which has been desorbed at nearly the waste heat source temperature, is passed through intercooler (d-1) and then is drawn into a mechanical compressor for high stage compression (1–2). The rest of the refrigeration cycle follows the same pattern.

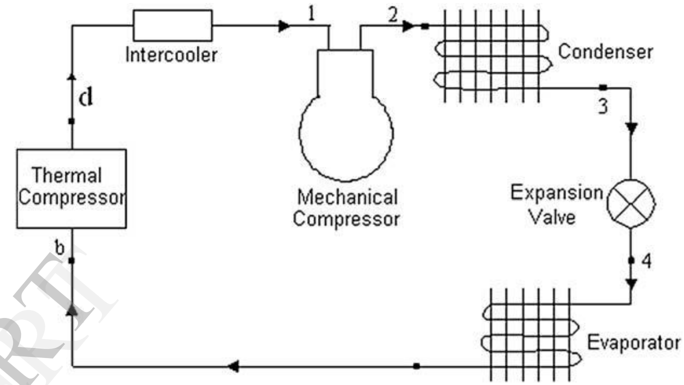

Fig 1: Schematic diagram of adsorption compressor hybrid refrigeration system.

The other possibility is to use the mechanical compression for the lower stage. Fig. 3 shows the schematic of the cycle and Fig. 4 on T–s and p–h planes. In this case, for the refrigerant and typical operating conditions chosen, there is no need for an after cooler as the refrigerant would exit at a temperature below the condensing temperature for a CO_2 system.

But, the extent of irreversible heating of refrigerant between the end of the evaporator and the start of compression process will be smaller than the previous case of high stage mechanical compression.

Another parameter that has been investigated is the inter-stage pressure

$[x = (p_{ev} \times p_{cond})^{0.5}]$ which is varied for $0.8 \leq x \leq 1.2$.

A major drawback of the above hybrid compression process is that the adsorption and mechanical segments have hugely different time constants. In contrast to cycle time of a few millisecond in case of mechanical compression, the adsorption part takes a few minutes to complete one compression cycle process. Hence, a series of sufficiently large adsorbers (usually four) will be required to ensure equal mass flowrate through each segment of compression

III. PERFORMANCE INDICATORS

The first indicator is conventional COP and is defined as follows:

COP=Refrigeration effect / (W_c + Q_{ad}) (1)

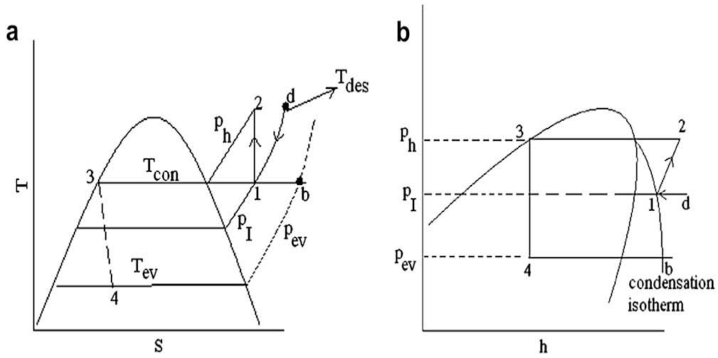

Fig 2: – Hybrid cycle with low stage thermal compression. (a) T–s plane. (b) p- h Plane.

The denominator here combines the work (mechanical stage, W_c) and heat (adsorption stage, Q_{ad}) quantities, which does not provide a true measure. Due to this, the heat quantity is changed to its exergy component using 298.15 K as the reference temperature (T_{ref}). Consequently,the refrigeration effect is also replaced and measured with the change in exergy of the refrigerant in the evaporator. The intrinsic COP is defined as:

COP intrinsic =ΔE_{ev} /[W_c+Q_{ad}{ 1-(T_{ref}/T_{des})}] (2)

whereΔ E_{ev} is the change in exergy of the refrigerant in the evaporator which given by:

ΔE_{ev} = m[(h_1-h_4)-T_{ref} (s_1-s_4)] (3)

An overall picture of efficacy of the hybrid cycle can be measured in terms of saving in power per kg of adsorbent used.

$$\Delta Wcomp = \frac{W_{c_1} - W_c}{m_{ch}} \qquad (4)$$

where W_{c1} is the mechanical compressor work, if the entire compression was carried out in a single stage. Evidently, W_{c1}–Wc is the conservation of energy due to compression supplemented by the thermal stage. For the simplifications of calculations, the isentropic efficiency is assumed to be 80%.

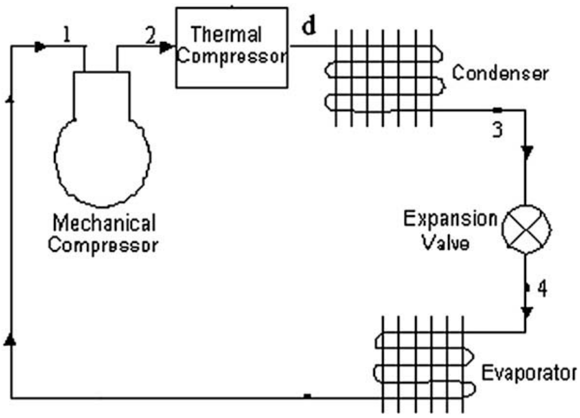

Fig 3: Schematic diagram of reverse hybrid refrigeration system

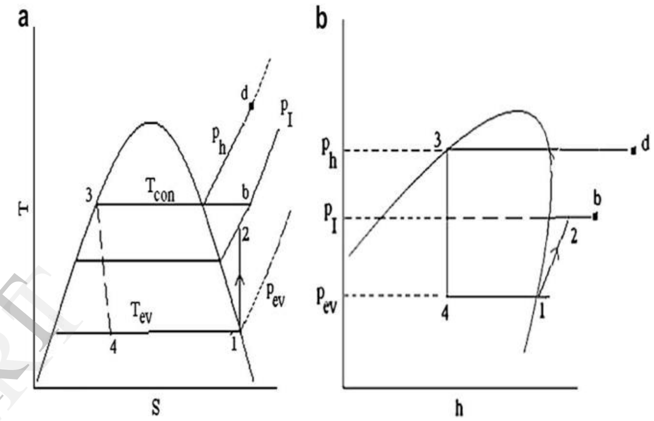

Fig 4: Reverse hybrid cycle with high stage thermal compression. (a) T–s plane. (b) p–h Plane.

The other indicators are the volumetric and uptake efficiencies, reduction in quantity of activated carbon used compared to single- and two-stage thermal compression. The volumetric efficiency of the mechanical compressor is calculated as follows (Arora, 1989) [21]:

$$\eta_{vcomp} = (1+c)\left(\frac{Psuction}{Pi}\right)^{1/m} - c\left(\frac{Pdischarge}{Pcon}\right)^{1/m} - 0.015\left(\frac{Pdischarge}{Psuction}\right)^{1/m} \qquad (5)$$

here, c is the clearance ratio (assumed to be 5%). The suction pressure is set at 95% of inlet pressure (which is p_e for low stage mechanical compression and p_i for the high stage) and that at discharge to be 103% of discharge pressure (which is p_{con} for the high stage compression and p_i for the low stage mechanical) to consider the pressure drops at suction and discharge ports and acceleration of refrigerant. The last term on the RHS of Eq. (5) takes into picture for leakages across the piston rings. The index m is taken as 1.2 for CO_2 .

Uptake efficiency of an adsorption compressor is analogous to the volumetric efficiency of a mechanical compressor and is defined as follows (Fig. 5):

η_{ul}= (C_b-$C_{a'}$)/(C_b-C_a) (6)

and η_{uh}= (C_f-$C_{e'}$)/(C_f-C_e) (7)

when adsorption compressor is in the lower (suffix l) or the upper (suffix h) stages, respectively. The data required for the analysis are the equation of state
for CO_2 adsorption characteristics of activated carbon and CO_2 system. The entire calculation scheme was programmed on a Matlab platform.

IV. RESULTS AND DISCUSSION

A comparison is made between single- and two-stage thermal compression, and the hybrid compression processes. There was a wide range of specimens which were covered and calculated for condensing/adsorption, evaporating and desorption temperatures, various packing densities of activated carbons and various specimens of activated carbon and a range of intermediate pressures. For discussion a particular case of t_{des} =80 ºC, t_{ad}= 30º C for Maxsorb specimen is presented. The packing density is taken as 315 kg/m3 in the absence of any other mention. A standard cooling load of 1 kW is the root of the discussion.

A. Coefficient of Performance

Fig. 6 shows a comparison of COP for single-stage, two-stage thermal compression and hybrid systems. It is noticed that: (i) The COP of a two-stage system remains roughly uniform over the entire range of evaporating temperatures investigated, (ii) single-stage system is better than the two-stage one for t_e > 6 ºC, and (iii) the hybrid cycle shows the highest COP because second stage which is mechanical compression, requires less energy.

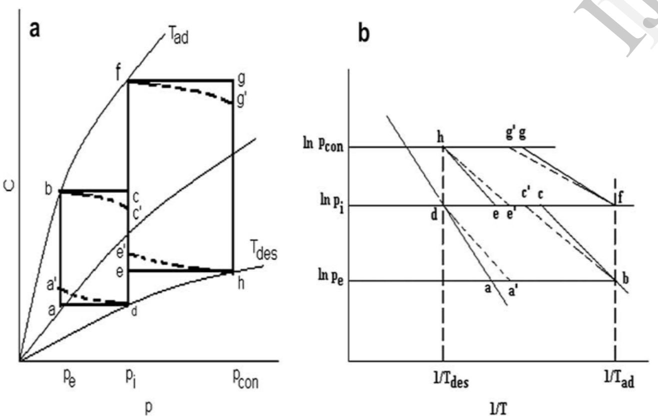

Fig 5: Thermal compression on p–c–T plane. Ideal cycles: a–b–c–d, low stage adsorption; e–f–g–h., high stage adsorption Real low cycles: a0–b–c0–d, stage adsorption ; e0–f–g0–h, high stage adsorption

B. Intrinsic COP

The exergy is a better tool to get useful information of cooling and the heat supplied to the thermal compressor, hence, when exergy is analysed, a better understanding of the thermal processes can be obtained. This is shown in Fig. 7.

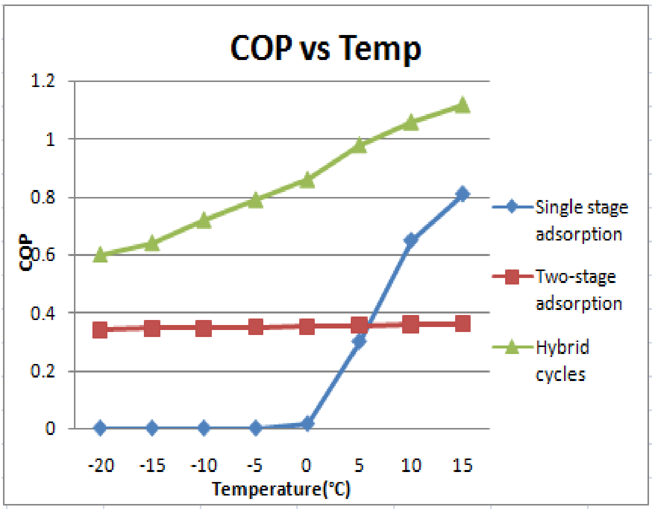

Fig 6 :Coefficient of performance at various evaporation temperatures

The single-stage intrinsic COP goes through a maximum identical to the maximum in ΔC vs exergetic efficiency as shown by [20]. This can be attributed to the adsorption characteristics of the activated carbon and CO_2 wherein ΔC varies almost linearly with evaporating temperatures for a specified adsorption and desorption temperatures. However, two-stage adsorption and hybrid systems demonstrate an appreciable improvement in intrinsic COP because of more compact adsorption compressors and reduction in heat inputs.

C. Uptake Efficiency

In Fig. 8 uptake efficiencies are juxtaposed and analyzed for single-stage, two-stage, hybrid and vapor compression cycle (volumetric efficiency). The case of ρ_{eff} =420 kg/m^3 for single-stage thermal compression is shown to demonstrate the qualitative improvement that is possible if packing density can be improved. As in case of ρ_{eff} =420 kg/m^3 , in single stage thermal compression, packing density plays a pivotal role. A qualitative improvement in packing density is clearly shown in Fig.8.

For the first and the second compressors in a two-stage system, and the hybrid system the uptake efficiencies are nearly equal to 1. This is because of a large ΔC that is available due to small pressure differentials across which it operates. For a single-stage system, at lower evaporating temperatures, the ΔC is relatively small which reduces the uptake efficiency and conversely at higher evaporating temperatures.Response of volumetric efficiency (in reciprocating compressor) congruent to uptake efficiency is also charted against evaporating temperatures. It can be inferred that the uptake efficiency can be improved by hybrid compression of the thermal stage significantly. Apparently, a single stage thermal compression would not have been possible for t_e < -10 ºC and there will be only a slight reduction even if the packing density is increased from 325 to 420 kg/m^3.

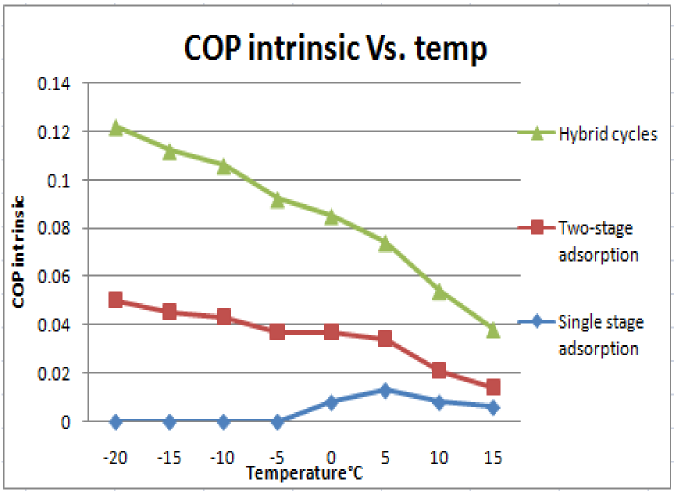

Fig 7: Variation of intrinsic COP with evaporation temperature

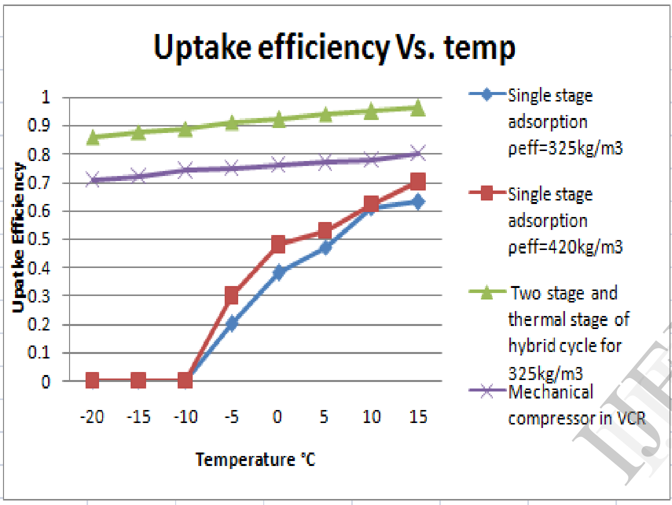

Fig 8 : Uptake efficiency variation for single-stage adsorption 325 kg/m^3, and 420 kg/m^3 two stage and thermal-stage of hybrid cycle for 325 kg/m^3 and mechanical compressor in VCR

D. Charcoal Requirement

Charcoal requirements are shown in Fig. 9. Charcoal requirement reduction is beneficial when the risks related to handling highly powdered solids is taken into consideration. Use of hybrid cycle substantially reduces the amount of charcoal required. The reason for reduction is the greater uptake efficiency and larger concentration differentials across the thermal compression stage.

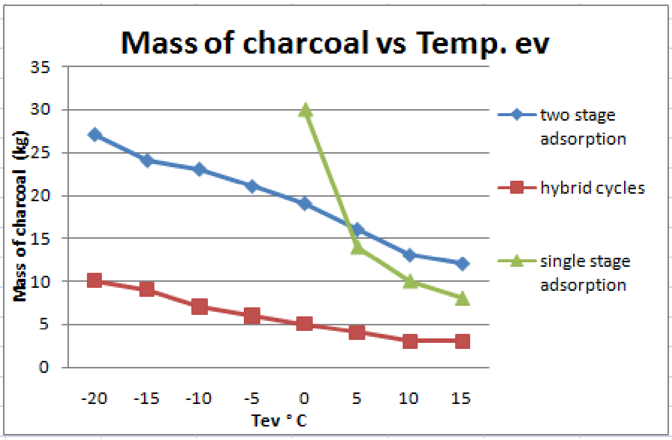

Fig 9: Activated carbon requirements for single stage, twostage adsorption and hybrid cycles

E. Mechanical compressor power

In Fig.10, a comparison is made over the shaft power requirement for the mechanical stage of hybrid cycle. The results were reported to be encouraging as it is documented that a saving of power >23% is possible.

The percentage savings stay in the same region but the absolute saving plummets marginally with reducing evaporating temperatures. Hence, hybrid refrigeration can become a mainstay in energy conservation in refrigeration systems.

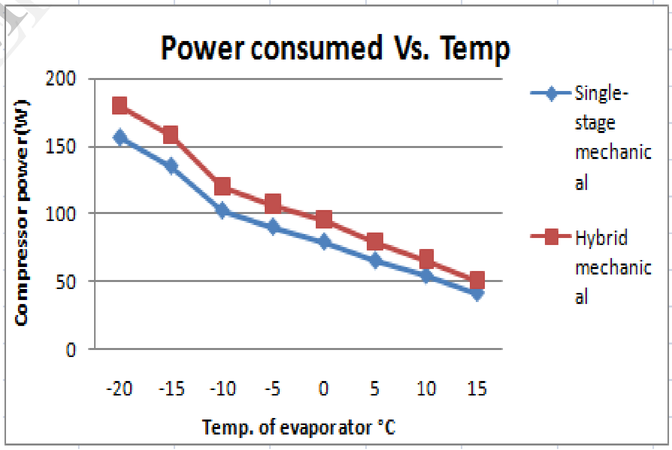

Fig10: Assessment of compressor power in hybrid and single-stage mechanical compression cycles

F. High Stage adsorption

The situation is a bit different when the mechanical compression(reverse hybrid) is employed in lower stage and upper cycle is left for the thermal compression as shown in Fig.12. There are two important points which need to be considered, firstly, the mechanical compressor power requirement for reverse hybrid cycle is lesser than the other. Secondly, the carbon requirement is higher for the reverse hybrid than the other. As a result one would expect COP and intrinsic COP would be inferior to those in low stage adsorption. But, the overall performance indicator (reduction

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in power per unit mass of carbon) of low stage compression is only slightly smaller than the other.

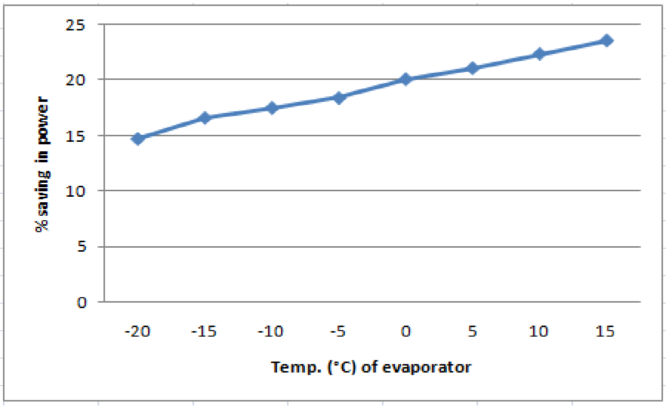

Fig 11. Percentage saving in compressor power in single stage an hybrid cycle

Although, these observations are applied for an interstage multiplier of 1 but it can be extrapolated to other multipliers too. These features can be explained as follows. The pressure differential across which the thermal compressor operates with high stage adsorption will be larger than when it is for the low stage, in spite of pressure ratios across each stage being the same. Resultantly, the void volume effect will be more dominating and therefore the uptake efficiencies will be decreased in a reverse hybrid case. A large carbon utilization will follow and hence effectively lower saving in power per unit mass of carbon despite the reduction in mechanical power

The difference narrows down and becomes insignificant at higher evaporating temperatures, which do not support a multistage compression in any case.

The thermodynamics related advantages have been established, yet some practical concerns for hybrid cycles still linger. One of them is the concern of oil carry over from the mechanical compressor. Oil separators are provided in larger systems. But in smaller capacity units designers rely on oil return by selecting refrigerant line velocities. There is danger of contamination of adsorption bed, thereby decreasing its performance. This problem will be abated to some extent if low stage adsorption compression is adopted.

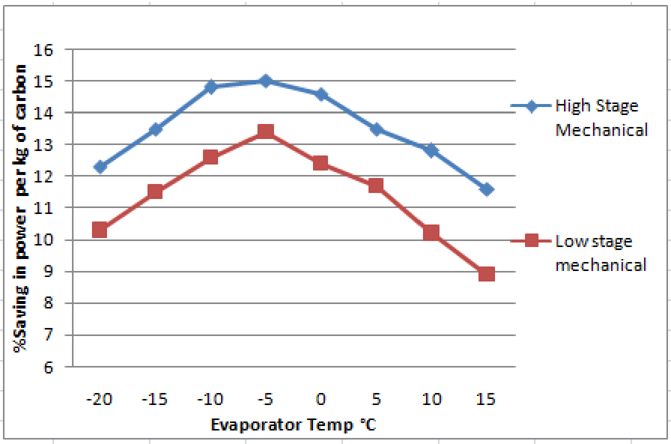

Figure 12: Comparison of hybrid cycles with low and high stages on the basis of % power saved per kg of carbon

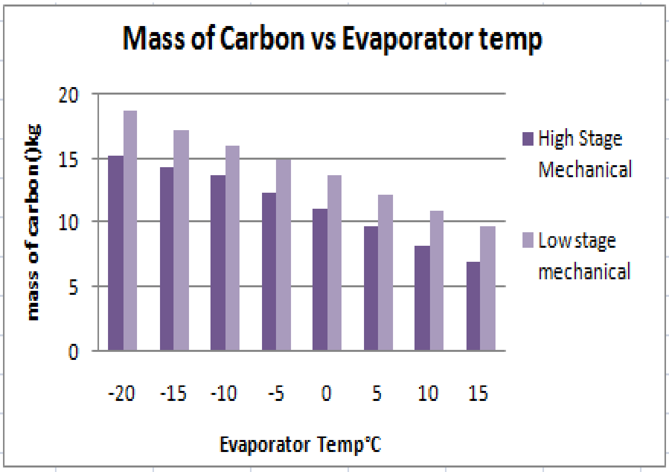

Fig.13:Comparison of hybrid cycles with low and High stages of mechanical compression

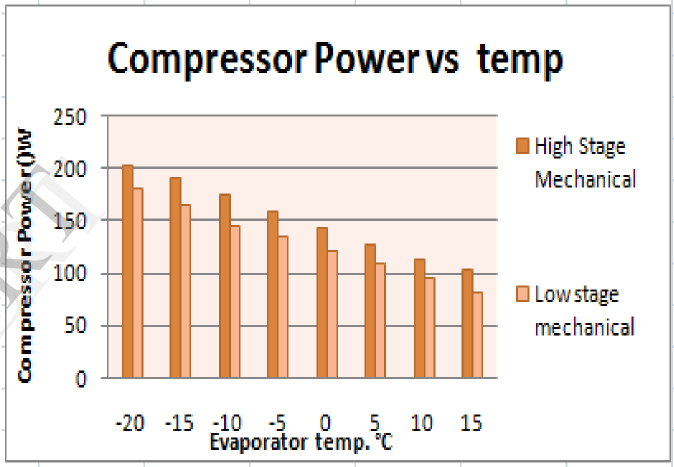

Fig 14: Comparison of hybrid cycles with low and high stages of mechanical compression for compressor power vs temp

V. Conclusion

When the temperature differentials are greater than room temperature, in that case, mechanical and thermal hybrid compression can definitely be considered as a successful option. The optimum interstage pressure remains at a conventional value applicable for multistage mechanical compression, with a progressive change to lower values as the evaporating temperatures reduce. On the basis of mechanical compressor work, it can be inferred that efficacy of hybrid system has come out to be worth considering for future avenues.

The low stage adsorption system fares better than the high stage on the performance front, even the interchanging between the low stage adsorption system and high stage system does not vary the results by appreciable margins.

These systems will generate realistic and actual benefits only when loads are extrapolated to few kilowatts. The supreme advantage of this system is the feasibility and application when low temperature thermal energy is available. This aspect could be utilized in process industries where a large amount of waste heat is available such as in thermal power plants and reduction of greenhouse gas emissions is of paramount importance.

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