Modification In Charging Composition In Order To Arrive At Desired Circulation Composition In The Context Of Sorption Compressor Based J-T Cooler

R. N. Mehta, S. L. Bapat, M. D. Atrey

Department of Mechanical Engineering, Indian Institute of Technology Bombay
Powai, Mumbai - 400 076

A sorption compressor based cooler works on thermal swing adsorption process followed by a Linde-Hampson cycle for producing the cooling effect. A mixed gas refrigerant provides low temperatures in the cryogenic range with pressure around 20 bar as compared to a high pressure of about 100 bar with a single pure working fluid such as Nitrogen. With gas mixture, the through put of individual gas in the sorption compressor varies from gas to gas. This is attributed to the different quantities of gases retained by the adsorbent at the end of desorption process. Therefore, in adsorption compressor, the mixture in circulation varies in composition when compared to the gas mixture composition while charging in the system. Necessary corrections in the mixture composition to be charged need to be incorporated so that the mixture in circulation has the desired composition. A mathematical model, based on the adsorption data for individual component gas is used to arrive at the correct composition of the gas mixture in circulation.

Key words: Sorption compressor, Mixed refrigerant, Charging composition, Circulation Composition

INTRODUCTION

Adsorption mechanism is generally categorized as physical adsorption, chemi-sorption, or electrostatic adsorption. Weak molecular forces such as van der Waal's forces act between the adsorbent and adsorbate. Physical adsorption is caused mainly by van der Waal's forces and electrostatic forces between adsorbate molecules and the atoms which compose the adsorbent surface. Thus, adsorbents are characterized mainly by surface properties such as surface area and polarity. The layout of the J-T cryocooler based on sorption/desorption process is shown in Figure 1. It consists of the major components as follows:

1. sorption compressor cells C1, C2, C3 and C4
2. connecting tubing with valves
3. after cooler
4. return gas Heat-exchanger
5. throttling device, and
6. evaporator

A sorption compressor cycle consists of heating, desorption with heating, cooling and adsorption with cooling shown as part A, B, C and D in Figure 2. Adsorption being an intermittent process for continuous operation of the compressor at least four cells are generally employed. Cell C1, C2, C3 and C4 are the four cells as shown in Figure 1. Each cell has suction and a discharge valve. Valves V1, V3, V5 and V7

are the suction valves and V2, V4, V6 and V8 are the discharge valves for the cells A, B, C and D respectively. All discharge valves and all suction valves are connected to corresponding manifolds. The discharge valve manifold is connected to the after cooler and suction valve manifold is connected to the return gas piping.

The temperature of the adsorbent is increased to T_H by switching on the electrical heaters. The rise in temperature leads to a decrease in the equilibrium adsorption capacity and the excess of gas is liberated. The liberated/desorbed gases inside the adsorber cell create a high pressure P_H in the enclosed volume.
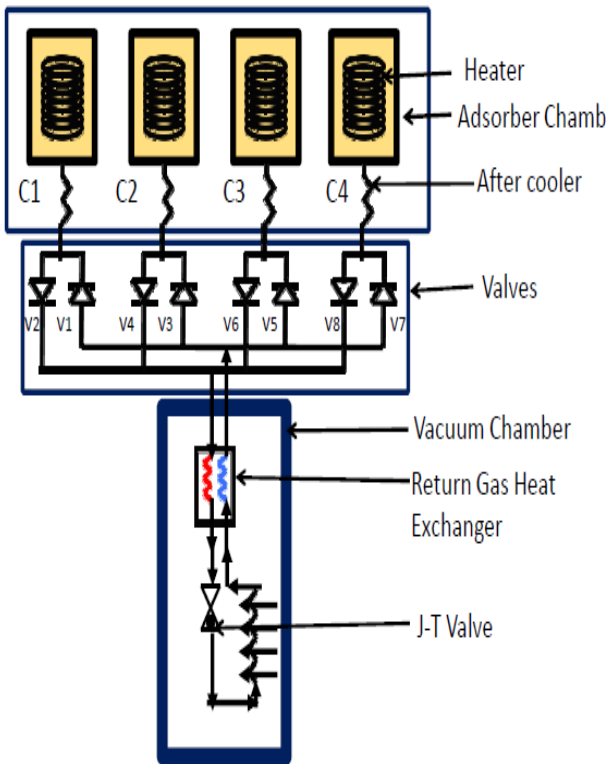

Figure 1. Layout of a Sorption Compressor based J-T cooler

The compression process is then followed by a controlled release of refrigerant from the desired high pressure. Thus, sorption compressor thermally compresses the refrigerant using Temperature Swing Adsorption (TSA) effect [2]. On expansion, low temperature is produced as in the Linde-Hampson cycle. In the present case, the adsorbent is heated using internally placed electrical heaters. P_L and T_L are the adsorption pressure and cooling temperatures of the compressor. The thermal conductivity of the adsorbent, in the present
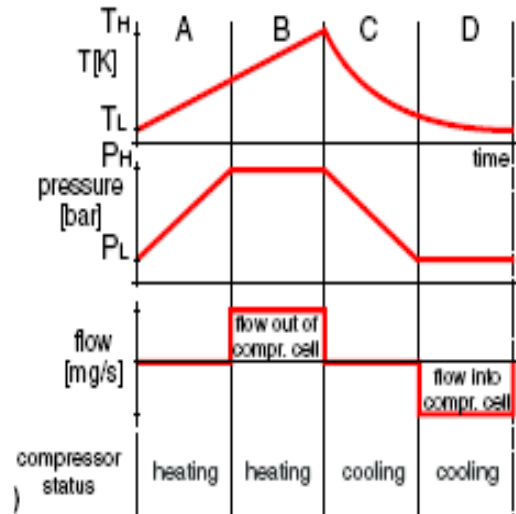

Figure 2. Various Process in continuous operation of a Sorption Compressor [3]

case, activated carbon, is considered to be poor and is around 0.15 W/m K [3]. Owing to this, a temperature gradient exists from the centre of the adsorber chamber to the outer periphery in radial direction in the cylindrical cells. The presence of the temperature gradient results in comparatively poor desorption at the locations where the temperature is lower. The poor desorption results in higher residual loading and as a result, this reduces the final high (discharge) pressure in the system and also the compressor throughput [4]. It is desirable to have the maximum length to diameter ratio for adsorption chamber in order to obtain a uniform temperature distribution [3].

THEORETICAL HIGH PRESSURE GENERATED DURING DESORPTION AND THE DESORPTION RATIO

In a sorption compressor, gases are desorbed by raising the temperature of the adsorbent. The highest possible pressure is achieved if all the adsorbed gases are desorbed and are present in the void volume inside the adsorber chamber. The pressure generated is estimated

using van der Waal's equation of state (equation 1).

$$\left(P + \frac{n^2}{v^2}\right)(v - nb) = nRT \qquad (1)$$

where *a* and *b* are the van der Waal's constants obtained from properties at critical point.

$$a = \frac{27(RT_C)^2}{8P_C} \qquad (2)$$

$$b = \frac{(RT_C)}{8P_C} \qquad (3)$$

The discharge pressure is directly a function of gas volume in the sorption chamber. In order to obtain a continuous high pressure stream, it is desired that a large quantity of gas should be adsorbed and at the same time, the void volume should be as low as possible to result in quick pressure rise and reduce loss of throughput. The gas temperature is assumed to be average of ambient temperature and heater surface temperature for these calculations.

CHOICE OF WORKING FLUIDS

The choice of the working fluid for a J-T cryocooler is arrived at based on the thermodynamic operating parameters of the cryocooler. These parameters are the required low temperature, desired refrigeration effect, and the high and low operating pressures. The properties of some of the refrigerants commonly used in cryogenics are listed in Table 1. To achieve a low temperature in the range of 80 to 100 K, a discharge pressure of the order of 100 bar is required in case of a pure substance like Nitrogen. However, a mixed refrigeration cycle, using a mixture of Nitrogen, Methane, Ethane, Propane, Iso-butane and R134a, high pressure requirement is in the range of 20 bar only. Also the mixed refrigeration cycle is characterized by a high heat transfer coefficient inside the return gas heat exchanger owing to change in phase of the mixture refrigerant on both hot and cold fluid sides. In the case of sorption compressor operating with a mixed gas refrigerant at a similar low temperature range, the presence of sub-critical hydrocarbons in the refrigerant improves the volumetric efficiency of the sorption compressor. The sub critical gases follow multi layer adsorption with or without capillary condensation, as per type III or V isotherm under the classification of International Union of Pure And Applied Chemistry (IUPAC) as shown in Figure 2. The ratio of maximum adsorption capacity to adsorption capacity at a particular condition is shown on Y axis against the concentration of the adsorbate. The higher adsorption capacity also facilitates the adsorption process to be carried out at near to ambient/room temperature. The criteria of selecting a working fluid in a sorption compressor type J-T cooler with respect to operating conditions are as follows:

- low temperature required
- pre cooling temperature
- inversion temperature of the cryogen
- limitations of high operating pressure
- flammability

The mixture components are to be so chosen that the normal boiling points are spaced, such that we can expect a continuous boiling and condensation process in the return gas heat exchanger.

The components should also have the following desirable properties with respect to the adsorption process.

- sufficient adsorption capacity to have a high discharge flow rate
- adsorbent affinity
- high thermal decomposition temperature
- lower critical pressure to ensure multilayer adsorption

An optimized mixture, providing the highest cooling capacity at a given temperature, will also result in a higher exergetic efficiency and high refrigerating effect per unit mass.

Desorption ratio
The specific energy required for desorption varies inversely with the quantity of gas adsorbed and also from one component to

other in the mixture considered. With cyclic operation, the gas mixture trapped in the void volume acts exactly in the same fashion as the gas in the clearance volume of a positive displacement compressor and is never discharged such as in the reciprocating compressor. Thus, a certain mass of gas mixture always remains inside adsorption chamber even in the desorbed state. This mass of gas retained inside the adsorber chamber is termed as the residual loading. The void volume of the adsorption cell is calculated by charging the helium in the system to desired pressure condition using helium adsorption method.

On account of residual loading, the composition of mixture desorbed will vary from the composition of the mixture charged. In order to arrive at the desired composition of mixture in circulation, it is essential that composition of the charging mixture is decided based on the residual loading for each gas. The ratio of mass of the gas desorbed and discharged to the mass of the gas in the adsorbed state is termed as the desorption ratio. The composition of charging mixture needs to be corrected based on the desorption ratio for each of the individual constituent gas.
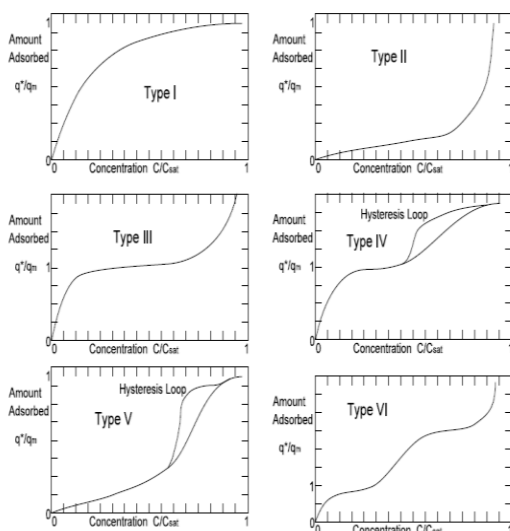

Figure 2. Types of Isotherms as per IUPAC

Mathematical model for arriving at desired composition of circulating mixture

Based on the desorption ratio, in order to have desired composition of mixture in circulation, the composition of the mixture to be charged is calculated as follows:

- The molecular weight of mixture is calculated based on the weighted average of the composition
- The mass of the gas necessary for generating a certain desired pressure is calculated using the van der Waal's equation of state
- Calculate the number moles of each gas required
- Based on desorption coefficients calculate the charging composition
- Calculate the number of moles of each gas
- Calculate the pressure at which the buffer chamber is to be charged, in order to accommodate the number of moles so as to generate the desired high pressure.

RESULTS AND DISCUSSION

Experiments were performed on single cell unit and two cell unit and it shows that the residual loading is different for different gases. Desorption ratio for Nitrogen, Methane, Ethane and R134a are experimentally determined and are shown in Table 2. Gases with lower boiling points like nitrogen follow mono layer Type–I adsorption isotherm as per IUPAC [5]. These gases have higher desorption ratio compared to the gases with lower boiling points. The working fluid in the present work is a mixture of high boiling as well as low boiling components.

The theoretical mass of the gas required for the desired high pressure is calculated based on the van der Waal's equation of state. In the present experimental set-up, the void volume using helium adsorption method is determined. The number of moles of the mixture and hence the moles of the individual component is calculated. This mass is the required mass of mixture in circulation. The mass of individual gas remaining in adsorbed

state after completion of desorption is calculated based on the desorption ratio of individual gas. The mass of the charging mixture is now calculated as the sum of the gas quantity in circulation plus the residual loading inside the adsorbed chamber.

The value of desorption ratio for ethane and propane is obtained by interpolation on critical temperature versus desorption ratio curve as shown Figure 3.
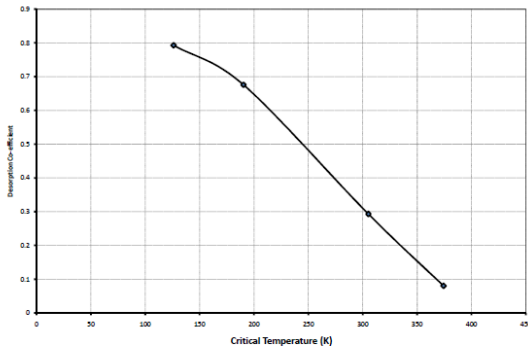

Figure 3. Desorption ratio curve for Nitrogen, Methane and R134a

Based on the developed mathematical model, the composition of the charging mixture for a selected mixture of nitrogen, ethane, propane and R134a with concentration 18.75, 23.25, 25 and 33 percentage respectively is as shown in Table 3. It is calculated that 390 grams of the mixture is required to obtain a discharge pressure of 18 bar. The corresponding charging composition is determined as 5.0, 16, 36 and 43. These are also shown in the Table 3.

CONCLUSIONS

The conclusion from the extensive experiments performed is as follows
• A fully operational sorption compressor based cooler is developed. The working substance used is a mixture of Nitrogen, Ethane, Propane and R134a in the concentration of 18.75: 23.25: 25: 33 percentage for circulating gas respectively.
• The high pressure developed in the experiment is around 14 bar. The adsorption pressure varies in the range of 3 to 5 bar.
• The composition of the mixture agrees reasonably with the predicted mixture composition in circulation, as measured with the gas chromatograph.

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Table 1 Physical properties of commonly used refrigerants in cryogenics

Gas	Critical Pressure (bar)	Critical temperature (K)	Molecular wt	Boiling point (K)	Latent heat kJ/kg
Nitrogen	34	126	28.0134	77.36	198.38
Methane	45.96	190.3	16.043	111	510
Ethane	48.84	305.2	30.069	184.3	488.76
Propane	42.5	369.6	44.096	230.9	425.31
R134a	40.6	374.3	102	246.4	215.9

Table 2 Desorption ratio for individual gases through experiments

Gas	Mass of gas charged	Mass of the gas in the cell void	Mass of the gas adsorbed	Theoretical Pressure	Actual pressure	Residual loading	Desorption ratio
Units	grams	grams	grams	bar	bar	grams	
Nitrogen	81.40	20.88	60.52	21.44	12.50	12.52	0.79
methane	51.78	9.07	42.71	23.33	15.50	16.78	0.68
R134a	2000.00	0.00	1500.00	31.90	6.90	1262.00	0.0.08

Table 3 Corrected charging mixture composition

Sr. No	Gas	Desired composition in circulation/operation	Mass (g)	Desorption ratio	Charge (g)	Moles	Charging composition
1	Nitrogen	0.1875	35.99	0.79	45.37	1.62	0.05
2	Ethane	0.2325	47.82	0.29	164.78	5.49	0.16
3	Propane	0.2500	75.41	0.14	538.68	12.24	0.36
4	R134a	0.3300	230.77	0.15	1488.84	14.59	0.43
	Total	1.0000	390.00			33.95	1.00