PAPER ID: XXXX
DOI: 10.18462/iir.compr.2024.0683

HEAT POWERED ADSORPTION COMPRESSORS FOR REFRIGERATION AND AIR-CONDITIONING APPLICATIONS

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ABSTRACT

In recent decades we witness a surge in electricity consumption rates, which escalates carbon dioxide emissions and increases global warming and other deleterious environmental impacts. Heat powered cycles are of great interest as they enable reduced electric power consumption. Ongoing research on thermally driven sorption compressors is being conducted in our research laboratory. In this research phase, a multi-stage sorption compressor for carbon dioxide is numerically investigated using a previously developed model. The model is dynamic and fully parametric, allowing for the analysis of nearly any cylindrical sorption cell with any heating and cooling method under various operating conditions. Multiple designs of adsorption cells and different heating and cooling methods have been evaluated to investigate sorption compressors. This paper presents four designs of sorption cells which we consider, a validation of the numerical model with carbon-dioxide, and numerical results a three-stage sorption compressor, which aims to compress carbon-dioxide from 5 MPa to 20 MPa.

Keywords: Refrigeration, Carbon Dioxide, Compressors

1. INTRODUCTION

Compressors are essential components in many cycles and processes. Global energy consumption has markedly increased over the past fifty years, from 230 EJ in 1971 to 636 EJ in 2021, an escalation of 276% (Alsouda *et al.*, 2023). The increase in energy demand requires an increase in energy production and energy transmission, resulting with a rise in costs and environmental effects (Sumeru *et al.*, 2019). This fact creates future challenges in planning the energy supply for many needs, and environmental concerns related to energy use (Dinçer and Rosen, 2015). Most of the heat pump systems, which make up a significant part of electricity consumers, operate by the vapor compression refrigeration cycle (Alsouda *et al.*, 2023), which consists of four key components: evaporator, compressor, condenser, and expansion valve. Sorption compressors are thermally driven (instead of being electrically driven) and can assist to reduce electric power consumption. These compressors can operate using solar radiation, biofuels, or waste heat. Moreover, sorption compressors benefit the absence of moving parts; meaning, they have the potential for long life and high reliability (Tzabar and Hamersztein, 2022), which make them attractive for space applications (Wu et al., 2017,Hamersztein and Tzabar, 2021,Tzabar and Hamersztein, 2022). Sorption compressors have been proposed for use in various applications, including Brayton cycles (Dutta *et al.*, 2014), air conditioning (Palomba *et al.*, 2019), and cryogenic cooling systems (Srinivasan and Dutta, 2019). A sorption cell is a closed vessel which includes a sorbent material and means for increasing and reducing the sorbent temperature. In recent study, we developed a simplified numerical model of cylindrical sorption cells, which was subsequently integrated into a comprehensive compressor numerical model (Hamersztein and Tzabar, 2021, Hamersztein et al. 2021). This numerical model is capable of simulating cylindrical sorption compressors with various numbers of compression stages and any number of sorption cells in each stage. Being dynamic and fully parametric, the model is adept at exploring a wide range of physical dimensions, construction materials, operating conditions, and it is suitable for any cylindrical sorption cell configuration, accommodating diverse heating and cooling techniques. The model has been successfully validated through comparisons with several experimental results of different sorption compressor configurations (Tzabar and Hamersztein, 2022). The current study phase aims to adjust the sorption compression technology for compressing carbon dioxide in refrigeration and air-conditioning systems. The numerical model is modified to comply with carbon-dioxide, and four designs of adsorption cells are examined, which differ by their heating and cooling techniques. A short validation of the modified model is presented, and preliminary numerical results of a three-stage compressor are demonstrated.

2. METHOD

2.1. Sorption compressor

Sorption compressors are based on the principle that a large quantity of gas can be physically or chemically adsorbed by an adsorbent. The current study focuses on activated carbon for physical adsorption, where the selected coolant is carbon-dioxide. The adsorption process is usually characterized by adsorption isotherms, which correlate temperature, pressure, and adsorption concentration. Figure 1 illustrates a sorption compressor cycle of a single cell. Figure 1(a) shows the pressure in the sorption cell as a function of time, and Figure 1(b) shows a cycle of the sorption cell on the adsorption isotherm plane. A heating process starts at state 1, which is characterized by low temperature, low pressure, and high adsorption concentration. An isochoric heating process, with closed valves, raises the pressure and temperature until theoretically reaching state 2. At state 2, the discharge valve is opened, and isobaric heating continues, allowing outflow of the working gas, until the cycle's maximum temperature at state 3 is obtained. Then, cooling begins with closed valves until the cell's internal pressure reaches the low-pressure at point 4 . Isobaric cooling continues with an open intake valve, allowing the working gas to flow from a low-pressure reservoir into the cell, thereby increasing the adsorption concentration, until the initial temperature at state 1 is reached, thus completing the cycle.

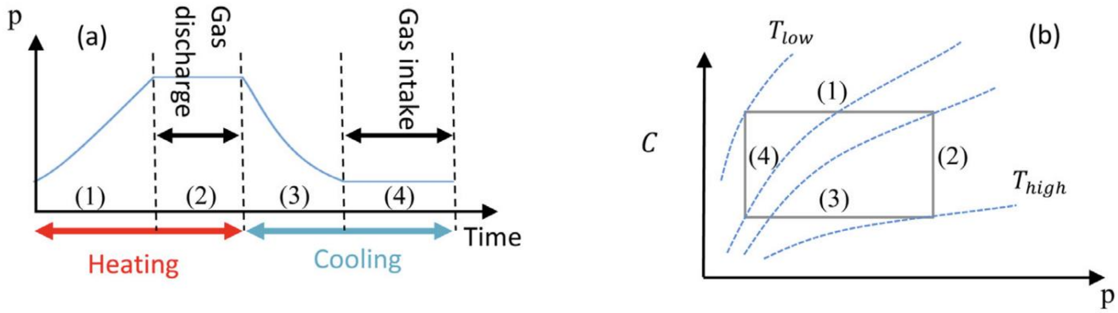

Figure 1: A single cycle of a sorption compressor cell: (a) cell's pressure versus time, (b) the cycle on the adsorption isotherms plane (Hamersztein and Tzabar, 2021)

In order to obtain a continues flow by a sorption compressor, several sorption cells are connected in parallel and operate in phase shift. Figure 2 illustrates a schematic of a compressor with i number of compression stages, and j_i parallel sorption cells in every i-th compression stage. A low-pressure buffer (LPB) and a high-pressure buffer (HPB) reduce the pressure oscillation in the low- and high- pressure lines, respectively. All stages are interconnected through passive intercoolers, designed to cool the fluid to the ambient temperature. It is essential to recognize that the pressure ratio in each compression stage is influenced by the adsorption isotherm characteristics.

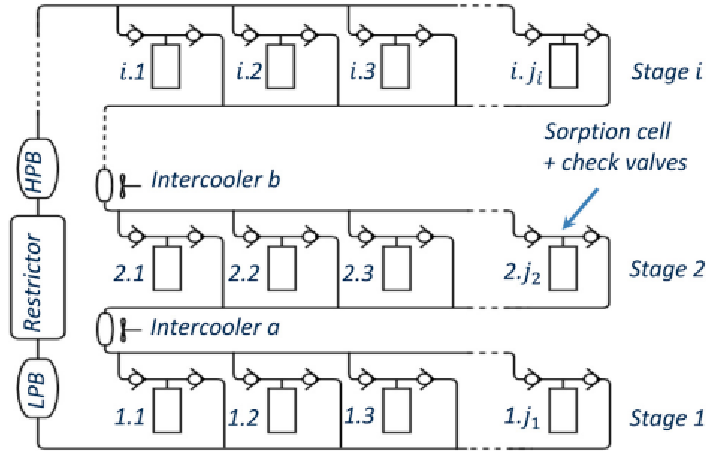

Figure 2 : A schematic view of a multi-stage sorption compressor (Hamersztein and Tzabar, 2021)**.**

This paper presents four designs of cylindrical sorption cells, with different heating and cooling techniques. Figure 3 shows a CAD model of a 'type-A' sorption cell, which contains an electric coil heater centrally located in the cell, and cooling is achieved by dissipating heat to the environment through the cell envelope. This configuration is constructed in our lab and described in detail elsewhere (Tzabar and Hamersztein, 2022).

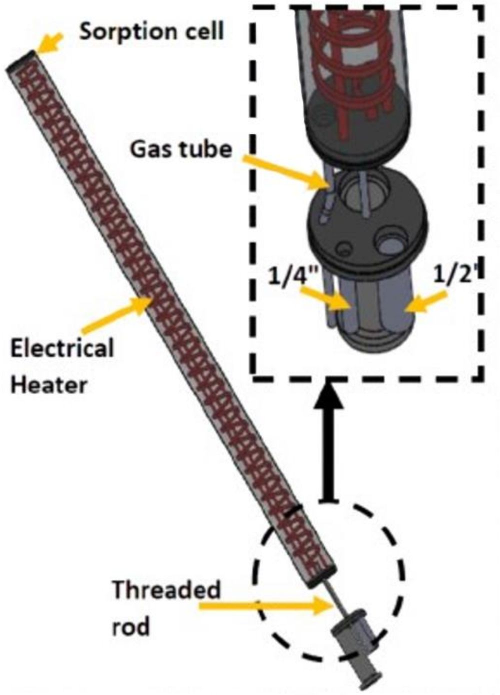

Figure 3: A CAD model of a ˈtype-Aˈ sorption cell (Tzabar and Hamersztein, 2022)**.**

Figure 4 shows a CAD model of a 'type-B' sorption cell, which incorporates two 1/4 inch U-shaped copper tubes for cooling, and a helical electric heater that is coiled around the cooling tubes. This configuration includes two Ham-Let check valves with a 1 psi cracking pressure, and the adsorption cell's envelope is insulated to minimize thermal losses to the environment.

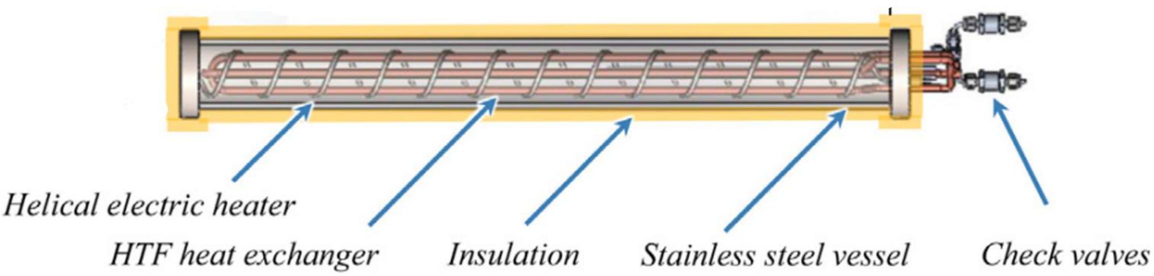

Figure 4: A CAD model of a ˈtype-Bˈ sorption cell (Hamersztein and Tzabar, 2021)**.**

Figure 5 shows a 'Type-C' configuration, where three ¼ inch U-shaped copper tubes are incorporated in the cell. The copper tubes are used both for heating and cooling the adsorbent, using hot and cold heat transfer fluids (HTF), respectively. Figure 5 (a) shows the copper tube manifold, together with the thermocouple's feedthrough which is located in the center of the cell, and Figure 5 (b) shows the complete sorption cell.

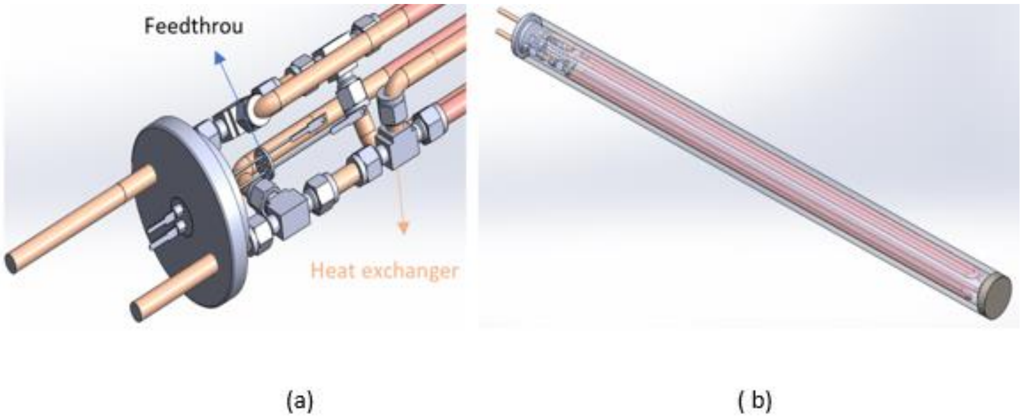

Figure 5: A CAD model of a ˈtype-Cˈ sorption cell.

Figure 6 presents a CAD model of the 'Type-D' sorption cell, which comprises of a stainless-steel outer cylinder where a HTF flows to heat and cool the adsorbent, which is located in four symmetrically arranged smaller cylindrical sorption cells. The HTF flow in the large cylinder, over the outer surface of the inner cylinders (which contain the adsorbent), in order to heat and cool it, according to the cycle stage. This configuration is already built in our laboratory and currently assembled to form a compressor, which shall be soon experimentally investigated.

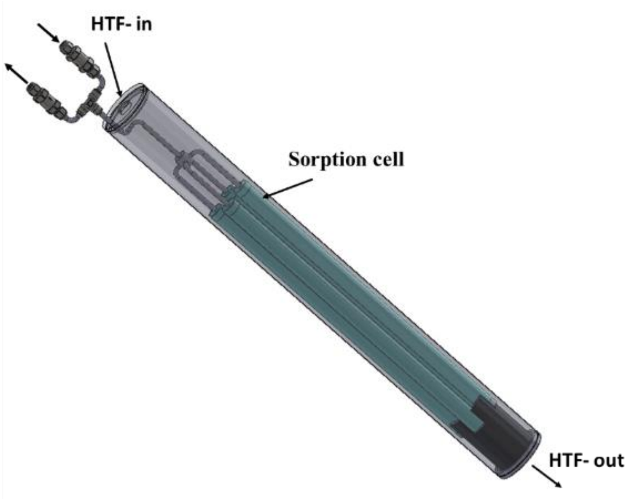

Figure 6: A CAD model of the type-Dˈ sorption cell.

2.2. Numerical model

A numerical model for multi-stage sorption compressors has been developed and presented elsewhere (Tzabar and Hamersztein, 2022). The model is dynamic and uses the finite differences method to calculate the state of all relevant parts in the compressor system assuming that the processes are quasistatic. The compressor model consists of a parametric one-dimensional numerical model, which is based on the energy and mass balance equations. The model simulates the pressure and temperature dynamics in the sorption cells, which undergoes thermal cycles and allows to change any physical parameter and operating conditions. The physical parameters include the dimensions and material properties of adsorption cells, buffers, and intercoolers, and the operating conditions including filling pressure, mass flow rate, ambient temperature, heating and cooling power and heating and cooling durations. Another important input to the numerical model is the adsorption isotherms of the working pair (adsorbent-adsorbate), and the fitting parameters to the Sips model (Tzabar and Grossman, 2011; Tzabar and ter Brake, 2016), as shown in Eq. (1):

$$\theta = \frac{C}{C_0} = \frac{(e_1.T^{e_2}.p)^{\frac{1}{n}}}{(1+e_1.T^{e_2}.p)^{\frac{1}{n}}} \qquad \text{Eq. (1)}$$

where p (MPa) is the pressure, C is the adsorption concentration, C_0 is the saturated adsorption concentration, both in $\left(\frac{mg_{adsorbate}}{g_{adsorbent}}\right)$, a is the adsorption affinity, and n is a dimensionless parameter that qualitatively characterizes the heterogeneity of the adsorbate-adsorbent system. $e_1$and e_2 are empirical parameters, and T(K) is the temperature. The adsorption isotherms are measured in our lab, and the Sips parameter are determined.

In previous work, experiments were conducted under different conditions to validate the numerical model against experimental results. The model was successfully validated against a 'type-A' sorption cell using nitrogen as the working gas. In the current study, the numerical model is adjusted for carbon dioxide, by incorporating its adsorption characteristics. A successful validation of the numerical model against the new experimental results was obtained, with a ˈtype-Aˈ sorption cell and carbon dioxide as the working gas. While results of types A and B are already published (Hamersztein and Tzabar, 2021; Tzabar and Hamersztein, 2022), the current paper presents preliminary numerical results of 'type-C' configuration, operating with carbon-dioxide, in the frame of our research on types C and D cells.

2.3. Results

Figure 7 shows calculated results (continuous lines) against experimental results (dashed lines) for a single ‘type-A’ sorption cell. The initial fill pressure is 2.**8** MPa and after **6** cycles, a steady state is obtained where the high pressure is relatively constant and equals 3.7 MPa and the low-pressure oscillates between 0.95–1 MPa. The compressor operates with low and high temperatures of 315 K and 720 K, respectively, and the flow rate equals 1.5 mg/s. A satisfying agreement between the calculated and experimental results is obtained, especially at the steady state operation.

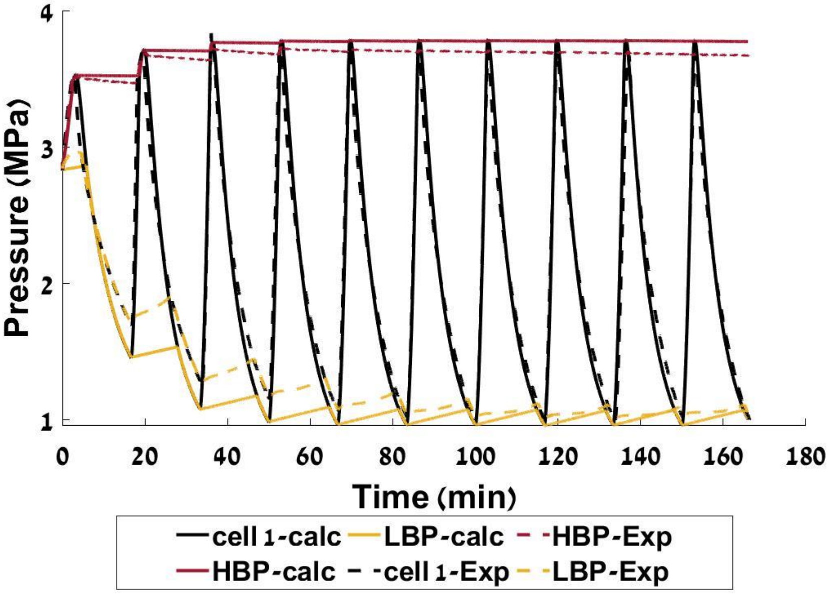

Figure 7: Experimental results (dashed lines) against calculated results (continuous lines) of a 'type-A' sorption cell.

Figure 8 shows numerical results for a three-stage compressor, which consists of 'type-C' adsorption cells. The presented case aims for compressing carbon-dioxide from 5 MPa to 20 MPa. The compressor contains three, two, and one cells, in the 1st, 2nd, and 3rd stages, respectively. The outer diameter of every sorption cell equals 3 inches, and the compressed fluid is carbon-dioxide. The initial fill pressure is 6.6 MPa, and after 11 cycles, a steady state is obtained where the high pressure oscillates between 21.1-18.2 MPa and the low-pressure oscillates between 4.4–4.8 MPa. The low and high temperatures in the cell center are 318 and 400 K, respectively, and the flow rate equals 50 mg/s. The average first intermediate pressure, between the first and second compression stages, equals 8.4 MPa, and the average second intermediate pressure, between the second and third compression stages, equals 13.6 MPa. Therefore, the pressure ratios of the first, second, and third stages are 1.8, 1.6 and 1.4, respectively.

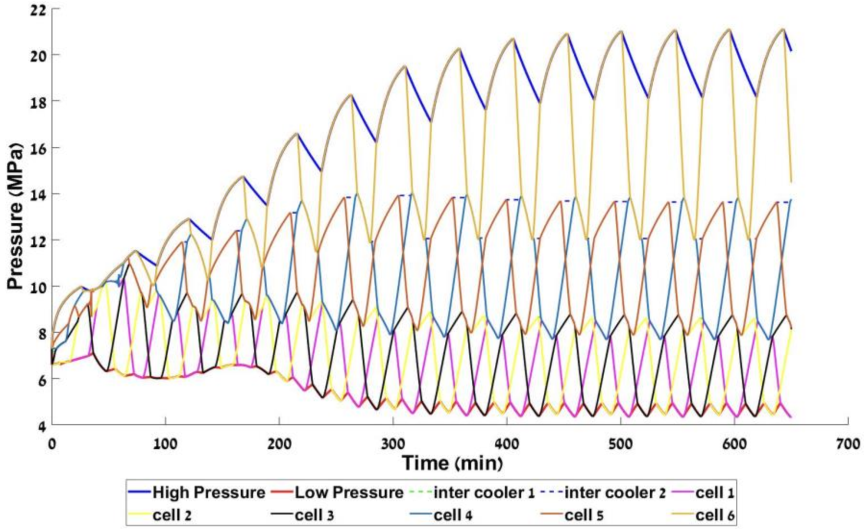

Figure 8: Calculated results of a three-stage compressor of six sorption cells, made of 3 inches tubes in diameter and 1300 cm in length. The compressed fluid is carbon-dioxide.

3. CONCLUSIONS

Sorption compressors are thermally driven and have no moving parts, except for some check valves. Therefore, sorption compressors are vibration-free, highly reliable, and with the potential for long life. Thermally driven compressors are of great interest in order to reduce electric power consumption, utilizing solar energy and waste heats as the driving energy. This study aims to investigate sorption compressors of different configurations and heating and cooling methods, for refrigeration and air-conditioning systems. A numerical model, which is developed in our lab, is dynamic, fully parametric, and allows the investigation of almost any cylindrical sorption cell, with any method of heating and cooling, and at any operating conditions. The model was calibrated according to relevant physical parameters and validated against experimental results of a ‘type-A’ sorption cell and carbon dioxide as the working gas. This paper presents a validation of the numerical model operating with carbon dioxide and a type-A sorption cell, showing sufficient agreement between the calculated and experimental results. In addition, numerical results of a three-stage adsorption compressor of ‘type-C’ configuration operating with carbon dioxide are presented. These findings emphasize the importance of a robust numerical model for effective design. The presented results in this paper are only preliminary outcomes of our research on incorporating sorption compressor technology to refrigeration and air-conditioning systems.

ACKNOWLEDGEMENTS

The authors acknowledge the Israeli Ministry of Energy for financially supporting our research on sorption Compressors for refrigeration and air-conditioning systems.

NOMENCLATURE

C	Adsorption concentration ($mg{\cdot}g^{-1}$)	HTF	Heat transfer fluid
C_0	Saturated adsorption concentration ($mg{\cdot}g^{-1)}$	HPB	High-pressure buffer
p	Pressure (MPa)	LPB	Low-pressure buffer
T	Temperature (K)		

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