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A 1-dimensional dynamic model for a sorption-compressor cell

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ABSTRACT

Sorption-based cooler is considered as an excellent candidate for the vibration-free cooling at cryogenic temperature. In a such cooler, the sorption compressor is the most critical module. To design a sorption-compressor, effective numerical models are essential which allow one to simulate the details of the heat and mass transfer within the sorption-compressor cell, predict the system performance and optimize various parameters. This paper presents a 1-dimensional dynamic model for a sorption-compressor cell, which is based on extensive adsorption-isotherm measurements and realistic thermal properties of materials at low temperatures. This numerical model combines the mass and energy equations while the momentum equation is skipped. It assumes the pressure to be uniform within the cell. However, the convection term in the energy equation is evaluated in this model with proper approximation without calculating the velocity field. A typical simulation case is presented to understand the details during a sorption compression that occur in the sorption-compressor cell. Experiments based on helium and neon operating at 77 K (liquid nitrogen temperature) were carried out to validate this model. The measured compressor performance was deviated from the simulation about 18%, but that is a reasonable inaccuracy for design propose and is well reasoned. Such 1-D dynamic model is qualified to be further used to design sorption compressor.

1. Introduction

Sorption-based cooling/heating technology has received much attention in recent years due to its unique advantages. It is attractive in the cryogenic temperature range to cool varies scientific instruments because it is vibration free, EMI free and it has a long lifetime [1]. The HVAC industry widely uses sorption-based technology for combined cooling, heating and power systems since sorption systems usually use environmentally-friendly refrigerants and are able to harvest low-grade heat [2].

The sorption compressor, also referred to as sorption pump in some applications where the operation pressure is below atmospheric pressure, is the core of the sorption cooling/heating system. A sorption compressor is based on the principle that a large amount of gas can be adsorbed physically or absorbed chemically by certain solids (sorbents) such as activated carbon, metal–organic frameworks (MOFs), praseodymium-cerium-oxide (PCO) or metal hydrides [3]. A sorption-compressor consists of one or several cells (also referred to as sorption beds) which basically are a pressurized containers filled with sorbent material and working fluid. By periodically heating and cooling the cell, one can create a pressure swing. Combined with check valves for maintaining the correct flow direction, the working fluid is then compressed/pumped from low pressure to high pressure, resulting in a mass flow that drives the cooling/heating cycle (e.g. Joule–Thomson cycle for cryogenic applications and vapor-compression cycle for air-conditioning).

To design an efficient sorption compressor, it is crucial to understand and optimize the transport phenomena including heat and mass transfer within the cell. However, a static, lumped model is usually applied in the system-level design [4,5]. Such a simplified model enables one to predict the performance and optimize the operation parameters of a sorption compressor. It is fully based on the energy balance of the sorption cell with the heat capacities and the sorption isotherms as the essential inputs. It can quickly give a first impression of the sorption compressor performance regarding its efficiency. It is also convenient to use the static lumped model for performing an optimization study on various operating parameters such as working fluid, operating temperatures and pressures.

A static lumped model does not include any dynamics of the compression cycle which actually is quite of interest to the developers. Therefore, many studies have been performed related to refrigeration or heat-pumping at room temperature based on a

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Nomenclature

Latin letters

b	van de Waals volume [m^3 mol^{-1}]
c	specific heat capacity (solid) [J kg^{-1} K^{-1}]
c_p	specific heat capacity at the constant pressure [J kg^{-1} K^{-1}]
D	diameter [m]
E	effectiveness of heat exchanger [–]
h	specific enthalpy [J kg^{-1}]
H	enthalpy [J]
k	thermal conductivity [W m^{-1} K^{-1}]
m	mass [kg]
M	molar mass [kg mol^{-1}]
p	pressure [Pa]
$\dot{Q}$	heat-flow rate (power) [W]
r	radius [m]
R	universal gas constant [J K^{-1} mol^{-1}]
t	time [s]
T	temperature [K]
$\underline{V}$	volume [m^3]
V	velocity vector [m s^{-1}]
x	amount normalized to the adsorbent mass [kg kg^{-1}]
Z	compressibility factor [–]

Greek letters

ρ	density [kg m^{-3}]
ϕ	porosity [–]
Ω	thermal expansion of the superheated liquid [K^{-1}]

Subscript

ads	adsorbed
b	bulk value (for porous material)
BF	buffer
cr	critical point
cell	sorption-compressor cell
CONT	container
eff	effective
fre	free gas
h	high
HS	heat-sink
HT	heater
ISL	insulation lay
l	low
nb	normal boiling point
p	in parallel
para	parasitic
s	in series
sor	sorber
tot	total
void	void volume

dynamic lumped model that solves the conservation equations of mass and energy [6–14]. A dynamic lumped model can predict the performance of the compressor more accurately and calculate the cycle time and the size of the compressor (which in general is proportional to the required amount of sorbent material). The information in the time domain given by the dynamic model allows one to further design the operational details, such as how to control the heating and cooling, how to stabilize the pressure and flow rate and how to synchronize multiple sorption cells. Furthermore, it also gives the possibility to design and optimize more complicated cycle system, for example, a multi-stage (cascading) sorption compressor and a multiple-bed regenerative sorption cycle [15,16].

In cryogenic cooling applications, the lumped model approach is not adequate since temperature gradients within the cell become relevant. In cryogenic applications heating is, usually, performed by electrical heaters rather than by a hot fluid heat exchange as is common practice in near-ambient applications. In order to establish a high efficiency, the electrical heating should be applied for a relatively short period of time so that the sorber is heated while only a minimum of heat is lost to the environment (heat sink). Consequently, large temperature gradients may be expected in a cryogenic sorption-compressor cell. These gradients will degrade the performance of the compressor: part of the compressor is too hot and part is too cold. To simulate the sorption compressor more accurately, a dynamic non-lumped model is needed. Bhandari et al. [17] built such a dynamic model for calculating the size and dynamic performance of the 20 K hydrogen sorption cooler for the Planck spacecraft. Burger et al. [18] developed a bondgraph model that simulated the temperature gradient in the sorption cell. This model was successfully applied in the design of a 4.5 K helium sorption cooler for space application. For room-temperature applications, Maggio et al. [19] composed a 2-dimensional dynamic model for the zeolite-water adsorption system. This model solved the mass and energy equations as well as the momentum equation considering the mass diffusion in the porous adsorbent. Thus it was able to provide profiles of the temperature, pressure and adsorption amount during the compression cycle, which is very useful information for understanding the heat and mass transfer phenomena within the cell. However, 1-dimensional dynamic model is adequate as long cylindrical sorbers are usually used for cryogenic sorption compressor. Such model can be well used for optimizing the dimensions of the cells in cryogenic sorption compressors.

For designing the sorption compressors within the cryogenic refrigerators, this paper presents a 1-dimensional dynamic model. Compared to Maggios 2-dimensional model, this model skips the momentum equation to reduce it into a 1-dimensional and it assumes the pressure to be uniform within the cell. However, the convection term in the energy equation is evaluated in this model with proper approximation without calculating the velocity field, whereas Bhandaris and Burgers models neglect the entire convection term as the conservation of momentum is neglected. The model is presented in detail in Section 2, and typical simulation results from this model are discussed in Section 3. Furthermore, the model is experimentally validated as is reported in Section 4. The paper closes with conclusions in Section 6.

2. 1-D dynamic model

This section presents the 1-D dynamic model for the sorption-compressor cell in detail. First, the basic configuration and operation process of a sorption-compressor cell for cryogenic cooling is introduced. Then assumptions and simplifications are discussed. The analytical description is presented, particularly for the adsorption part of the cycle. Finally, additional information, such as meshing, discretization, algorithm and material properties, is given.

2.1. Basic configuration of a sorption-compressor cell

The model presented in this paper is based on the sorption-compressor-cell configuration that is schematically shown in