Joule-heated reactor structures for the electrification of direct air capture

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Highlights

- Direct air capture (DAC) is a promising way to create negative CO_2 emissions.
- Joule heating was used to electrify DAC, reducing heating costs of the desorption step.
- A gyroid structure was used to minimize pressure drop over the reactor

1. Introduction

Combating climate change is one of the major challenges for humanity in the 21st century. According to the IPCC, Direct Air Capture (DAC) and similar technologies will play a major role in solving this issue. Not only can they be used to reduce net CO_2 emissions, but they can also help correct a potential overshoot in global temperature rise by enabling negative emissions [1]. However, in its current state, DAC is not economically viable due to its high energy costs and low TRL. In this research, we address this issue by combining solid-phase DAC with Joule heating. This enables uniform heating of the reactor, reducing the process's energy cost relative to conventional heating. Moreover, by shaping the sorbent into a gyroid structure, we avoid high pressure drops that would typically be associated with packed-bed reactors. This facilitates scale-up of the process. By combining experimental tests with a numerical model, we will provide a proof of concept at the laboratory scale and predict the potential for future scale-up.

2. Methods

To make the samples, a paste of zeolite 13X and binders is shaped into a gyroid structure. The gyroid structure was chosen because it has a significantly lower pressure drop than the packed bed at equal sorbent holdup, as shown in Figure 1. A Kanthal wire is inserted through the sorbent structure, thereby making the sample electrically conductive. Due to the Joule effect, applying a current to the sample causes it to heat volumetrically due to its electrical resistance.

On the modelling side, a 1D homogeneous Python model is used to predict the full Temperature-Vacuum Swing Adsorption (TVSA) cycle, as typically implemented in a solid-phase DAC. This consists of the following stages: adsorption, blowdown (pressure reduction), preheating, desorption, and pressurization. The full cycles were run until the cyclic steady state was reached.

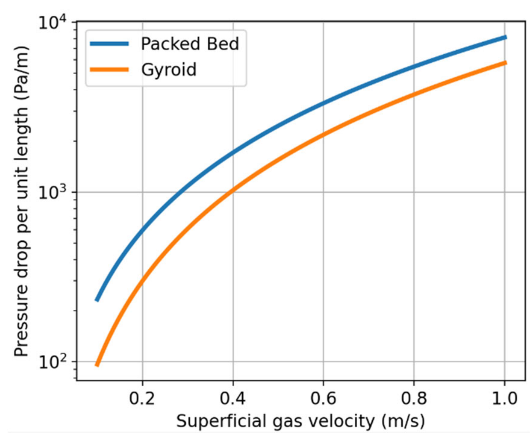

Figure 1: Comparison between pressure drop of a packed bed (Ergun equation) and a gyroid structure (based on [2]) for various feed velocities.

3. Results and discussion

One of the samples fabricated in the lab is shown in Figure 2. The gyroid structure is clearly visible. By varying the cell size (i.e., the size of the smallest repeating unit) and the wall thickness of the sample, the porosity can be tuned.

The model (see Figure 3) shows that applying Joule heating at larger scales can significantly reduce the cycle time of the TVSA process. Due to the faster and more uniform heating, CO_2 is desorbed more quickly, and fewer heat-transfer limitations are present in the process. Productivity consequently increases significantly, while the specific energy required decreases.

	Wall heating	Joule heating
Productivity ($kg_{CO2}/m^3/day$)	33	95
Electric energy needed (MJ/kg_{CO2})	1.7	1.1
Heating energy needed (MJ/kg_{CO2})	63	24

Table 1: Comparison of the productivity and energy requirements for the wall heating and Joule heating case shown in Figure 3.

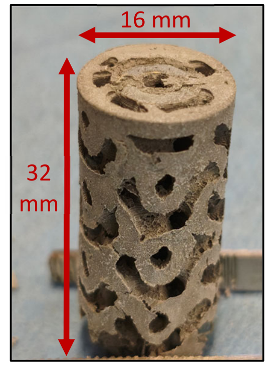

Figure 2: A gyroid sample

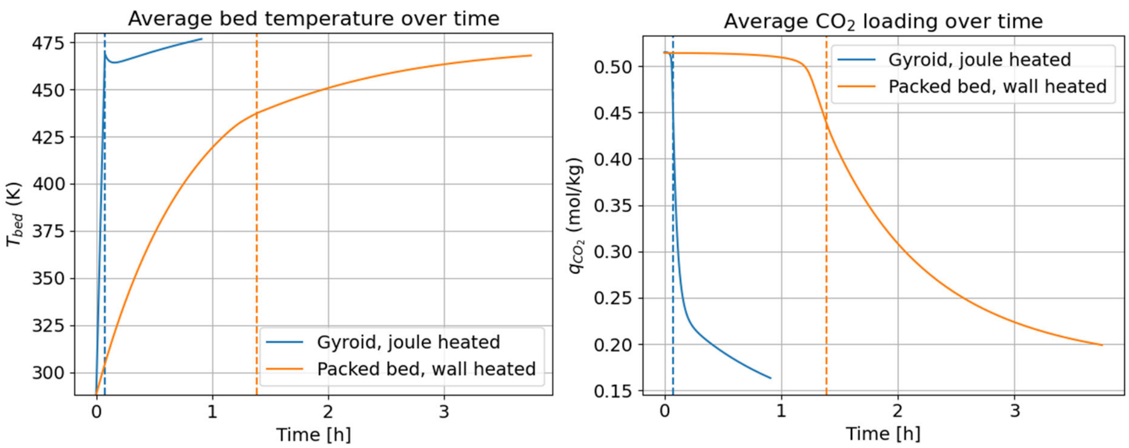

Figure 3: Comparison of CO_2 desorption in a wall-heated packed bed and a Joule-heated gyroid structure.

4. Conclusions

Joule heating can make direct air capture more cost-effective by enabling more uniform heating of the reactor, thereby increasing productivity and reducing specific energy consumption. Lab-scale samples were fabricated as a proof of concept, and modelling efforts have demonstrated the potential for Joule heating at larger scales. Further research will focus on extending this concept to other sorbents, identifying optimal process parameters, and conducting a cost-benefit analysis of this method.

References

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Keywords

Direct air capture; electrification; Joule heating.