Coupling a CO_2 plasma with a carbon bed: the closer the better

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Abstract: This study presents detailed kinetic modelling of a CO_2 gliding arc plasmatron (GAP) coupled with a carbon bed (C-bed), validated and compared with experiments. The model reveals that the C-bed enhances reactor performance by converting O_2 to CO_2 while promoting the reverse Boudouard reaction, enriching CO output at high temperatures. This coupling significantly boosts the industrial viability of CO_2 valorization.

1. Introduction

Plasma-based CO_2 conversion can drive endothermic reactions using renewable electricity, making it a suitable option for sustainable fuel production. However, its energy efficiency is often limited by recombination reactions that regenerate CO_2 [1]. Coupling plasmas with a C-bed addresses this by removing O_2 and enhancing CO_2 conversion through the reverse Boudouard reaction (RBR) [2], $C(s) + CO_2(g) \rightleftharpoons 2\ CO(g)$, with $\Delta HR° = 172$ kJ/mol (1), which exploits plasma-generated heat, otherwise dissipated to the reactor walls and wasted.

In this study, we refine plasma-C-bed coupling by optimizing the plasma-to-carbon distance, achieving 41.5% CO_2 conversion and 2.8 eV/molecule energy cost. Our detailed kinetic model reveals that the performance improvement stems from enhanced heat transfer for RBR.

2. Methods

We test a CO_2 gliding arc plasmatron (GAP) coupled with a C-bed filled with biochar and compare three reactor geometries: Reactor A (10 mm gap between plasma and C-bed), Reactor B (plasma separated by a 1 mm mesh), and Reactor C (direct plasma-carbon contact).

The kinetic model, adapted from [3], is calibrated using thermal gasification experiments, with adjustments to surface reaction rates to reflect material differences. The model is then run over the experimental parameter space and the outcome is used to gain insights into the underlying kinetic mechanisms.

3. Results and Discussion

Figure 1 compares the CO_2 conversion and energy cost across different reactor geometries. Reactor C, without mesh (which obstructs close plasma-carbon contact) clearly improves performance, making the technology competitive with other more established CO_2 conversion methods.

Our model suggests that a better plasma-carbon interaction does not directly improve performance due to quenching of recombination reactions through O_2/O removal from the product stream. Instead, this interaction promotes combustion reactions, reforming CO_2. The positive effect of close contact arises from the higher temperatures sustained at the C-bed, aided by exothermic combustion reactions. These high temperatures then drive RBR, converting CO_2 to CO and counteracting the fast combustion kinetics.

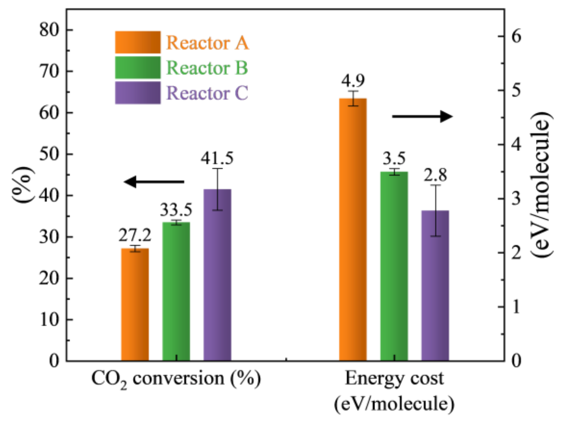

Fig. 1. Comparison of CO_2 conversion and energy cost among different reactors (CO_2 flow rate = 5 L/min).

4. Conclusion

Improving the plasma-carbon contact shows great potential for achieving high CO_2 conversion, highly concentrated, O_2-free CO output, and low energy costs, i.e., all features highly desirable for industrial applications. Our optimized GAP reactor, with these modifications, achieves over 40% CO_2 conversion and an energy cost below 2.8 eV/molecule. The model demonstrates that closer plasma contact promotes RBR, counteracting recombination into CO_2. Future work should focus on maintaining high temperatures, especially when coupling a C-bed with plasmas with high CO_2 dissociation degrees, to sustain high conversion outputs.

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