Analisis Sensitivitas Sistem Direct Air Capture Karbon Dioksida Siklus Steam-Assisted Temperature-Vacuum Swing Adsorption dengan Adsorben APDES-NFC = Sensitivity Analysis of Carbon Dioxide Direct Air Capture Steam-Assisted Temperature-Vacuum Swing Adsorption Cycle with APDES-NFC Adsorbent

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Abstrak

Latar Belakang: Peningkatan konsentrasi karbon dioksida (CO2) di atmosfer akibat aktivitas manusia mendorong perlunya teknologi penangkapan karbon yang efektif untuk mencapai target Net Zero 2050. Direct Air Capture (DAC) menjadi solusi potensial, terutama untuk sektor emisi difus. Akan tetapi, teknologi ini masih terkendala oleh kebutuhan energi yang tinggi, khususnya energi termal. Optimalisasi sistem DAC diperlukan guna meningkatkan efisiensi dan kelayakan operasional. Tujuan: Penelitian ini bertujuan untuk mengoptimalkan sistem Steam-Assisted Temperature Vacuum Swing Adsorption (S-TVSA) pada DAC dengan menganalisis dan mengevaluasi pengaruh berbagai parameter operasional terhadap konsumsi energi dan kinerja adsorpsi CO. Metode: Penelitian dilakukan menggunakan pendekatan simulasi numerik berbasis pemodelan matematis satu dimensi untuk sistem DAC tipe S-TVSA. Model kinetika adsorpsi CO dan HO pada material APDES-NFC diformulasikan menggunakan isoterm GAB dan modified Toth, serta laju perpindahan massa berbasis Linear Driving Force (LDF). Simulasi transien dan analisis sensitivitas terhadap parameter operasional kemudian dikakukan untuk mengidentifikasi variabel kunci yang memengaruhi performa sistem, menggunakan perangkat lunak MATLAB sebagai platform komputasi utama. Hasil: Hasil simulasi siklus DAC S-TVSA menunjukkan total specific energy requirement 71,96 MJ/kg CO2 yang ditangkap untuk kondisi operasional tekanan desorpsi pL = 0,05 bar, laju alir uap Fs = 25 cm3/s, dan waktu desorpsi t = 30000 detik. Produktivitas CO2 yang rendah (0,0002535591 kg) pada simulasi sejalan dengan skala sistem yang dirancang (panjang kolom 0,1 m). Kesimpulan: Simulasi sistem DAC dengan pendekatan S-TVSA menunjukkan bahwa model isoterm GAB dan Tóth termodifikasi sesuai untuk menggambarkan perilaku adsorpsi HO dan CO pada material APDES-NFC. Waktu desorpsi optimum ditemukan pada 15.900 detik dengan produktivitas CO tertinggi dan specific energy 51,044 MJ/kg. Tekanan desorpsi rendah (30 mbar) terbukti lebih efisien dibandingkan tekanan tinggi dalam hal produktivitas dan konsumsi energi.

......Background: The increase in atmospheric carbon dioxide (CO2) concentrations due to human activities is driving the need for effective carbon capture technologies to achieve the Net Zero 2050 target. Direct Air Capture (DAC) is a potential solution, especially for the diffuse emissions sector. However, this technology is still constrained by high energy demands, especially thermal energy. Optimization of the DAC system is necessary to improve efficiency and operational feasibility. Objective: This study aims to optimize the Steam-Assisted Temperature Vacuum Swing Adsorption (S-TVSA) system on DACs by analyzing and evaluating the influence of various operational parameters on energy consumption and CO adsorption performance. Methods: The study was conducted using a numerical simulation approach based on one-dimensional mathematical modeling for S-TVSA type DAC systems. The CO and HO adsorption kinetics model in APDES-NFC material was formulated using GAB and modified Toth isotherms, as well as Linear

Driving Force (LDF)-based mass transfer rates. Transient simulation and sensitivity analysis of operational parameters were then stiffened to identify key variables affecting system performance, using MATLAB software as the main computing platform. Results: The results of the DAC S-TVSA cycle simulation showed a total specific energy requirement of 71.96 MJ/kg CO2 captured for the operational conditions of desorption pressure pL = 0.05 bar, vapor flow rate Fs = 25 cm3/s, and desorption time t = 30000 seconds. Low CO2 productivity (0.0002535591 kg) in the simulation is in line with the scale of the designed system (column length 0.1 m). Conclusions: Simulation of DAC systems with the S-TVSA approach shows that the modified GAB and Tóth isothermal models are suitable to describe the adsorption behavior of HO and CO in APDES-NFC materials. The optimum desorption time was found at 15,900 seconds with the highest CO productivity and specific energy of 51,044 MJ/kg. Low desorption pressure (30 mbar) has been proven to be more efficient than high pressure in terms of productivity and energy consumption.