Studies on Green Adsorbents and Optimization Strategies for Adsorption Refrigeration System

The global energy demand, particularly for cooling, refrigeration, and air-conditioning, has been rising rapidly, correlating with the standard of living, which is also responsible for a high amount of greenhouse gases (GHGs) harming the environment and climate change. Thus, there is a need for effective utilization of waste thermal energy including renewable fuels and resources to reduce escalating energy demand, thereby mitigating the climate change. The cooling requirements for refrigeration and air-conditioning contribute significantly to global energy consumption, expected to triple by the mid of this century. Approximately 17% of global electricity is consumed by conventional cooling and heating systems, primarily reliant on fossil fuels, leading to resource depletion and greenhouse gas emissions. Moreover, many remote areas face challenges due to electricity scarcity, posing challenges for conventional refrigeration and air-conditioning for critical applications like food storage and preservation of life-saving drugs. The depletion of fossil fuels, environmental concerns, and challenges in remote areas intensify the urgency to develop sustainable technologies, drawing attention to ecological and renewable energy resources.

In countries like India, surplus biomass is often burnt in-situ, contributing to resource wastage, air pollution, and environmental degradation. Converting crop residues into value-added products could serve as a mitigation strategy against biomass wastage and in-situ burning. Alongside improving energy efficiency and biomass waste management, alternative heat-powered cooling technologies are essential to reduce grid dependency for refrigeration and air-conditioning. The adsorption technology has emerged as the promising solution, operating on low-temperature heat sources like Solar thermal, geothermal energy, and biomass combustion heat, and ensuring lower maintenance due to fewer moving parts. However, challenges such as bulky systems and high operating costs have hindered the commercialization of adsorption technology. Despite these setbacks, advancements in adsorber designs, novel adsorbents, multi-stage schemes, heat and mass recovery schemes, and control mechanisms offer avenues for enhancement. This thesis contributes to advancing adsorption refrigeration systems through experimental and numerical studies, aiming to optimize parameters, improve efficiency, and pave the way for a more sustainable and commercially viable cooling technology.

An extensive literature survey highlights a huge variation in the thermal performance of adsorption refrigeration systems with different porous materials. Therefore, a thermal performance estimation of a single-stage vapour adsorption system using various carbon-based adsorbents with ethanol refrigerant has been studied. The system is coupled with a small-scale biomass-based heating unit for space cooling, refrigeration, and heat pumping applications. The detailed investigation explored the impacts of operating parameters, and heat exchanger to adsorbent mass ratio on specific cooling energy (SCE), coefficient of performance (COP), uptake efficiency (η_u), and mass of adsorbent to combustion fuel to identify the suitable adsorbent and sorption bed designs for each application. One of the promising biomass-based adsorbents with finned flat-tube adsorbers outperforms traditional designs by 19-30%. Further, biomass-based adsorbents not only demonstrate superior performance, with higher COPs and efficiency for heat-pumping applications, but also require the least amount of adsorbent to achieve the desired effect per unit mass of combustion fuel in biomass heating units.

The thermal performance enhancement of an advanced adsorption chiller involves a comprehensive assessment focusing on entropy generation minimization through appropriate operating strategies, temperatures, and design modifications. The analysis involved a second law evaluation of a two-bed silica gel water pair-based adsorption cooling system, exploring novel aspects like heat recovery and measures to reduce auxiliary consumption. The specific irreversibility index, reflecting entropy generation, auxiliary electricity consumption, and cooling capacity, serves as an indicator for second law efficiency. The numerical evaluation shows around 63% reduction in entropy generation with a passive heat recovery strategy, and up to 22% decrease in specific irreversibility with a capillary-assisted evaporator. Additionally, a multi-objective optimization is conducted considering wetness fraction and hot flushing effects, employing the NSGA II and LINMAP techniques. The research findings highlight the substantial contributions of precooling, preheating, and flushing processes to exergy destruction, emphasizing the importance of a heat recovery scheme. The proposed optimized values of COP and specific exergy destruction (e_D) under passive heat recovery indicate improvements of +18.56% and -27.63%, respectively, compared to a system without heat recovery.

The crop residue management in India, marked by the longstanding issue of in-situ burning causing climate change, health concerns, and soil degradation, is a critical challenge. Simultaneously, adsorption refrigeration faces obstacles in commercialization due to bulkiness and inadequate performance linked to unsuitable adsorbents. To address both concerns, the present study focused on green synthesis, detailed characterization, and sustainable application of porous activated carbons derived from abundant crop residues. The optimized biochar, activated with KOH, exhibits substantial surface areas of 2002 m^2/g for sugarcane bagasse (SBAC) and 1241 m^2/g for rice straw (RSAC), surpassing commercial activated carbons. These novel activated carbons exhibit superior performance, notably in ethanol uptake, making them promising candidates for efficient and sustainable cooling and heat-pumping applications in renewable energy-powered systems. The proposed SBAC-ethanol pair demonstrates higher effective uptake and energy density compared to similar adsorbents, showcasing the potential of synthesized activated carbons. This research recommends the proposed activated carbons as promising candidates for efficient and sustainable cooling and heat-pumping applications, offering a potential solution to both crop residue management challenges and the enhancement of adsorption refrigeration technology.