ME – PhD Thesis Colloquium

Experimental and Numerical Studies on Salt Hydrate-Based Closed Loop Thermochemical Energy Storage System

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ABSTRACT

Thermochemical energy storage (TCES) utilizes reversible solid–gas reactions to store thermal energy with high energy storage density, negligible standby losses, and strong potential for long-duration and seasonal heat storage. These characteristics make TCES particularly attractive for low- and medium-temperature applications such as space heating and waste heat recovery. In a TCES system, thermal energy is stored during an endothermic charging (dehydration) process and released during an exothermic discharging (hydration) process, with the reaction direction governed by temperature and water vapor pressure.

The present research focuses on the design, modelling, and experimental validation of a closed-cycle TCES system for heating applications. A comprehensive review of thermochemical materials identified salt hydrates as the most suitable class for low-temperature operation. Among them, potassium carbonate (K_2CO_3) was selected due to its chemical stability, operational safety, single-step reversible reaction, and favourable charging and discharging temperature ranges compatible with building heating systems.

Following material selection, a closed-cycle TCES concept was developed consisting of a packed-bed reactor (energy storage bed) and an integrated evaporator–condenser unit for vapor management. As reactor performance is governed by coupled heat transfer, vapor transport, and reaction kinetics, a scaling analysis was first conducted to identify the dominant length and time scales controlling the charging and discharging processes. Using an order-of-magnitude analysis of mass, momentum, and energy conservation equations, critical thermal diffusion and vapor penetration length scales were derived. The analysis revealed the existence of inactive regions within the reactor bed beyond these critical scales, where the reactive material does not participate effectively in the reaction. These scaling relations provide a general and systematic framework for reactor design and are applicable to a wide range of gas–solid thermochemical systems.

To further investigate transport-reaction coupling at the reactor scale, a two-dimensional numerical model was developed using a finite volume approach. The model solves the coupled equations governing vapor flow through porous media, heat transfer, and reaction kinetics for potassium carbonate hydration and dehydration. Numerical simulations confirmed the predictions of the scaling analysis, demonstrating that incomplete conversion arises from limitations in thermal diffusion and vapor transport beyond critical geometric dimensions. The numerical results validated the robustness of the scaling framework and provided quantitative guidance for reactor geometry and heat exchanger design.

Based on insights from the scaling analysis and numerical modelling, a laboratory-scale closed-cycle TCES prototype with a storage capacity of approximately 3 MJ was designed and constructed. The reactor employs a shell-and-tube configuration, with geometry and vapor flow paths selected to avoid inactive regions within the reactive bed. Experimental investigations during charging and discharging demonstrated stable and controllable system operation. The results highlight vapor pressure as the primary control parameter governing reaction rates, temperature evolution, and heat release during the discharging process. The experimental findings validate the proposed design methodology and confirm the effectiveness of the integrated scaling-numerical-experimental approach.

Overall, this work establishes a unified framework for the systematic design of closed-cycle thermochemical energy storage systems, bridging material selection, theoretical scaling, numerical analysis, and experimental validation. The outcomes provide practical design guidelines and a strong foundation for further optimisation and scale-up of salt hydrate–based TCES systems for building heating applications.

ABOUT THE SPEAKER

Kartik Jain is a PhD scholar in the Department of Mechanical Engineering at the Indian Institute of Science (IISc), Bangalore, working under the supervision of Prof. Pradip Dutta and Prof. Susmita Dash. He joined IISc in January 2019. He completed his B.E. in Mechanical Engineering from Shri Shankaracharya College of Engineering and Technology, Bhilai, Chhattisgarh, in 2014, and obtained his M.Tech. in Thermal Engineering from IIT Delhi in 2016. His research focuses on Thermal Energy Storage systems, Thermal System Design, Computational Fluid Dynamics (CFD), Thermodynamics, and Heat Transfer.