ME – PhD Thesis Defense

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 density and negligible standby losses, making it attractive for long-duration thermal storage applications such as space heating and waste heat recovery. In TCES systems, thermal energy is stored during an endothermic charging (dehydration) process and recovered during an exothermic discharging (hydration) process, with the reaction direction governed by temperature and water vapor pressure.

The present doctoral research focuses on the design, modelling, and experimental evaluation of a closed-cycle TCES system for low- and medium-temperature heating applications. A comprehensive assessment of thermochemical storage materials identified salt hydrates as a promising material class for such applications, and potassium carbonate (K_2CO_3) was selected based on its favourable operating temperature range, chemical stability, reversibility, and suitability for low-temperature heat storage and recovery.

A closed-cycle TCES configuration comprising a packed-bed reactor and an integrated Evaporator–Condenser (E/C) unit was developed. A transport-based scaling analysis was first performed to identify the dominant heat and vapor transport mechanisms governing reactor performance. Characteristic thermal diffusion and vapor penetration length scales were derived using order-of-magnitude analysis. Under representative hydration conditions, the critical thermal diffusion length and vapor penetration depth were estimated to be approximately 8 mm and 40 mm, respectively. The scaling analysis indicated that reactor dimensions exceeding these characteristic transport scales can result in underutilization of the reactive material and was used to provide preliminary criteria for reactor design. A two-dimensional transient numerical model was subsequently developed to resolve the coupled heat transfer, vapor transport, and reaction kinetics within the reactive bed. The simulations demonstrated that increasing the reactor dimensions beyond the characteristic thermal and vapor transport scales progressively increases heat-transfer and vapor-transport limitations, leading to incomplete reaction progression. The numerical results further established the influence of reactor geometry and operating conditions on reaction rate, extent of conversion, and reactor utilization.

Based on these analyses, a laboratory-scale closed-cycle TCES system containing approximately 4.7 kg of potassium carbonate-based reactive material and having a nominal storage capacity of approximately 3 MJ was designed, fabricated, and experimentally evaluated. During charging (dehydration), the peak charging power increased from approximately 475W at an HTF inlet temperature of 95 °C to approximately 860 W at 115 °C. A representative charging cycle stored approximately 2.77 MJ of thermal energy, corresponding to about 85% of the theoretical storage capacity. During discharging (hydration), peak heat output reached approximately 245 W, with peak discharging powers of approximately 110–250 W over the investigated operating range and approximately 2.47 MJ of heat recovered in a representative cycle. The experimental results demonstrate that vapor pressure strongly influences the hydration reaction rate, vapor transport, and heat output, while heat transfer within the packed bed remains the dominant limitation on overall reactor performance. Repeated hydration–dehydration cycling produced an initial conditioning effect, with peak discharging power increasing from approximately 125 W at cycle 8 to 205 W at cycle 23, after which the performance approached a relatively stable state.

Overall, the present work establishes an integrated analytical, numerical, and experimental framework for the design and evaluation of closed-cycle thermochemical energy storage reactors. The derived transport scales, numerical analysis, and experimental results provide practical guidance for reactor geometry and heat-transfer design and establish a foundation for further optimization and scale-up of salt hydrate-based TCES systems for building heating applications.

ABOUT THE SPEAKER

Kartik Jain is a PhD scholar in the Heat Transfer Lab, 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 his M.Tech. in Thermal Engineering from IIT Delhi in 2016. His academic and research experience has primarily focused on thermal sciences, with an emphasis on energy storage and thermal system development. His research interests include thermal energy storage systems, computational fluid dynamics (CFD), thermodynamics, and heat transfer.

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