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REVIEW ARTICLE

REACTOR ENGINEERING OF SALT-HYDRATE THERMOCHEMICAL HEAT TRANSFORMERS FOR INDUSTRIAL WASTE-HEAT UPGRADING: A SYSTEMATIC REVIEW

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ABSTRACT

Low- and medium-temperature industrial waste heat below about 200 °C remains an underutilised energy resource because its temperature is often too low for direct reuse. Salt-hydrate thermochemical heat transformers (TCHTs) have been investigated as a means of upgrading this heat through reversible gas-solid hydration and dehydration reactions. This systematic review examined reactor engineering aspects of salt-hydrate TCHTs, including reactor configurations, reaction-transport modelling, reactor performance, exergy, techno-economic considerations and technology readiness. The review was conducted in accordance with the PRISMA 2020 guideline. Relevant publications between 2012 and July 2026 were identified through searches of Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink, and relevant MDPI journals, and 30 studies met the predefined inclusion criteria. The literature indicated that reactor engineering has become a greater challenge to practical deployment than material selection alone. Packed-bed, fluidised-bed and moving-bed reactors were compared in terms of heat and mass transfer, operating characteristics and suitability for continuous operation. Among the reactor concepts reviewed, crossflow moving-bed reactors appeared to offer the greatest potential for industrial waste-heat upgrading, although the available evidence is still based largely on modelling studies. Experimental validation under industrial operating conditions, reactor-scale exergy analysis, techno-economic assessment and consistent performance reporting remained limited. These areas require further investigation before the technology can be evaluated confidently for large-scale industrial application.

1.0 Introduction

Industry accounts for a large share of the world's energy use, and much of that energy leaves the process as waste heat that is never recovered (Forman *et al.*, 2016). Estimates of how much of this heat could realistically be reused vary with the accounting method, but the studies agreed on one point: low- and medium-temperature streams below roughly 200 °C make up the largest and most neglected share (Forman *et al.*, 2016; Miró *et al.*, 2016). These streams are usually too cold to reuse in the same process, so some form of temperature-lifting step is needed first. Mechanical heat pumps can do this, but they run on electricity and the temperature lift they can deliver is limited (Rahbari *et al.*, 2025). Thermochemical heat transformers operate differently because they use a reversible gas-solid reaction. Waste heat is stored during the endothermic charging step and released during the exothermic discharging step at a higher temperature than the temperature at which it was captured. The process is driven by heat rather than electricity (Rahbari *et al.*, 2025; Hayatina *et al.*, 2023).

Salt hydrates reacting with water vapour are among the more promising working materials for this task (Hayatina *et al.*, 2023; Hua *et al.*, 2022; Li *et al.*, 2022). They store a reasonable amount of energy per unit weight and volume, dehydrate at temperatures close to what industry actually rejects as waste heat, and many

candidate salts are cheap and only mildly toxic (Hayatina *et al.*, 2023; Li *et al.*, 2022; Spietz *et al.*, 2025). Even so, after many years of materials-focused work, reactor development has not progressed at the same pace as materials development. Problems related to reactor operation continue to limit practical application, leading several researchers to conclude that the reactor, rather than the material, is now the main bottleneck (Pan and Zhao, 2017; Kur *et al.*, 2023; Li *et al.*, 2022). This review therefore kept the reactor at the centre, with particular attention to the moving-bed design that has become the leading option for continuous industrial use, and places one recent, industrially targeted modelling study (Sefidgar *et al.*, 2026) in the wider materials and reactor literature instead of treating it in isolation. Figure 1 illustrates the two-reactor cycle: waste heat drives dehydration during charging, and the dehydrated salt releases stored heat at a higher temperature during discharging with humid air.

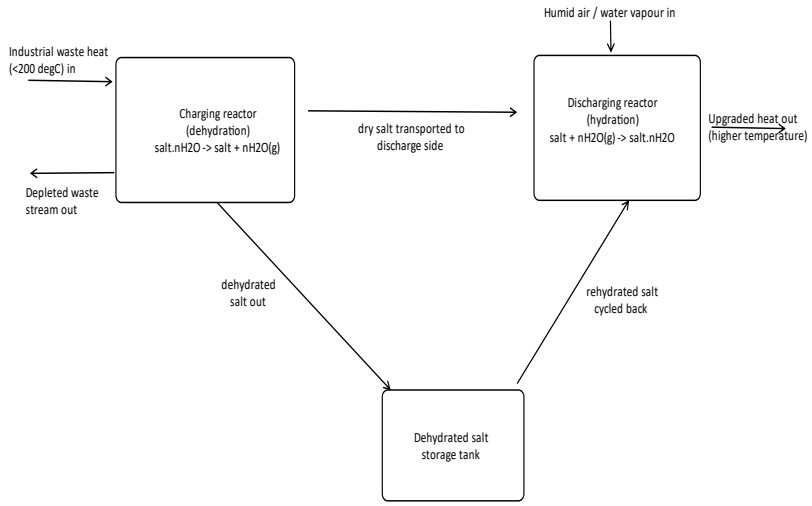

Figure 1: Schematic of the two-reactor thermochemical heat transformer (TCHT) charging/discharging cycle.

2. Method

The electronic search was conducted between March and July 2026 using Boolean search strings. A representative search string was: ("thermochemical heat transformer" OR "chemical heat transformer") AND ("salt hydrate" OR "thermochemical energy storage") AND ("moving-bed reactor" OR "packed-bed reactor" OR "fluidised-bed reactor") AND ("industrial waste heat" OR "waste-heat upgrading").

The search was limited to English-language publications. Studies were included if they reported original experimental, numerical, or techno-economic investigations on salt-hydrate thermochemical heat transformers, with emphasis on reactor design, operation, modelling, or performance. Studies focusing only on sensible heat storage, latent heat storage, adsorption systems unrelated to salt hydrates, or lacking sufficient reactor-level information were excluded.

The search identified 168 records. After duplicate removal and title, abstract, and full-text screening, 30 studies met the eligibility criteria and were included in the review. The studies were assessed for relevance, methodological quality, and completeness of reported reactor performance before being synthesised according to thermochemical materials, reactor concepts, modelling approaches, reactor performance, exergy analysis, techno-economic assessment, and research gaps. The study selection process is summarised in Figure 2.

3. Findings of the Review

3.1 Thermochemical Materials for Heat Transformation

3.1.1 Salt Hydrates as thermochemical materials

A thermochemical material (TCM) used for heat transformation undergoes a reversible reaction of the general form salt. $nH_2O(s) \rightleftharpoons salt(s) + nH_2O(g) \pm \Delta Hr$. The forward step, dehydration, absorbs heat and was driven by the lower-temperature waste stream; the reverse step, hydration, releases heat, and this heat comes out at a higher temperature once the dehydrated salt meets humid air again (Hayatina *et al.*, 2023; Clark *et al.*,

2022). Screening studies had compared candidate salts on energy density, equilibrium temperature at atmospheric pressure, cyclability, cost, availability and toxicity, and of several hundred candidates only a small number survived this screening for heat upgrading in the 150-300 °C range (Hayatina *et al.*, 2023; Hua *et al.*, 2022; N'Tsoukpoe *et al.*, 2014). Among the salts most frequently identified in screening studies were $CaCl_2$, $SrCl_2$, $MgCl_2$ and $SrBr_2$. These chlorides and bromides were consistently selected because they combined suitable equilibrium temperatures with favourable reaction kinetics and maintained acceptable performance over repeated hydration–dehydration cycles (Li *et al.*, 2022; Spietz *et al.*, 2025; N'Tsoukpoe *et al.*, 2014).

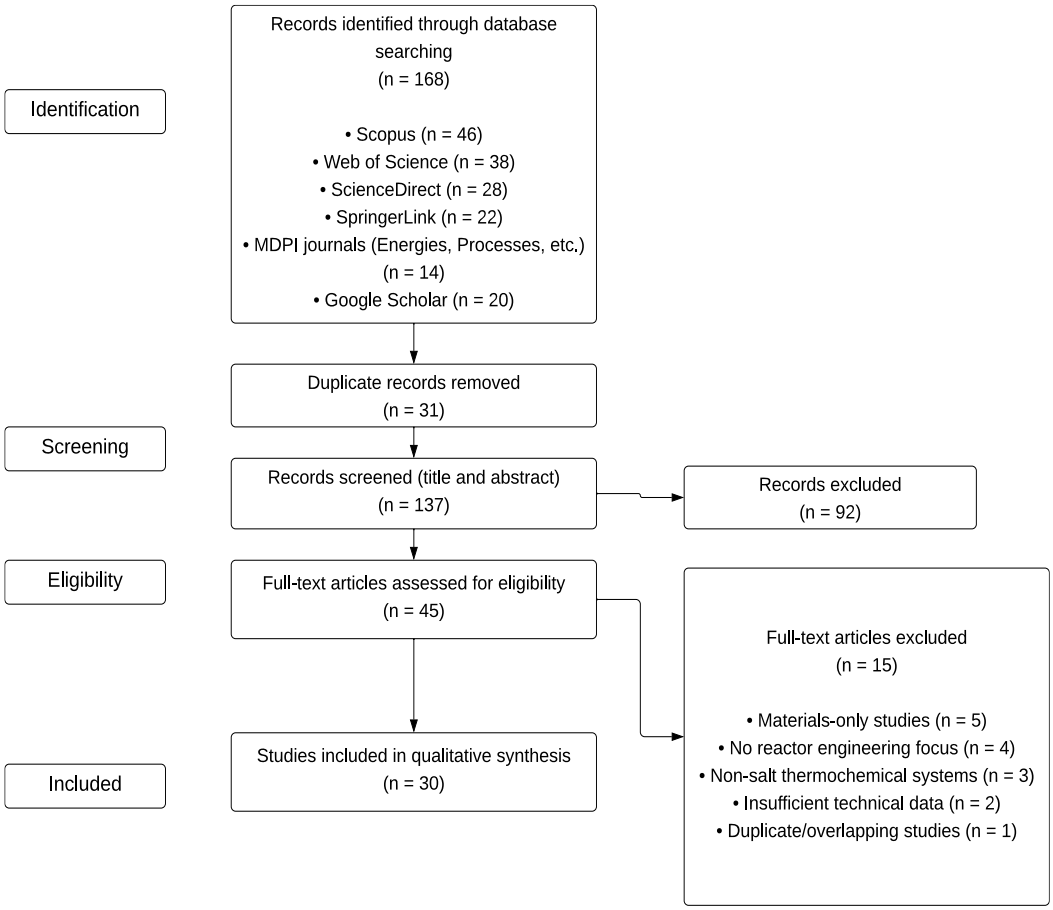

Figure 2: Flow chart illustrating the literature selection process

3.1.2 Deliquescence and moisture-related degradation

Reaction speed alone does not decide how a TCHT reactor can be run. A second constraint, deliquescence, limits practical operation. If a salt sits in air with a relative humidity above its own deliquescence relative humidity (DRH), it absorbs more water than the hydration reaction needs and turns into a liquid solution rather than remaining solid (Li *et al.*, 2022; N'Tsoukpoe *et al.*, 2014; Mukherjee *et al.*, 2022). Because DRH depends jointly on local temperature and vapour pressure, deliquescence can occur in a small part of a bed even when average conditions look safe, typically at the coolest point where incoming humid air first meets dry salt (Sefidgar *et al.*, 2026). Once this happens, particles clump, vapour pathways close off, and reactive surface area is lost; bed porosity and permeability change irreversibly, degrading every subsequent cycle (Li *et al.*, 2022; Hua *et al.*, 2022; N'Tsoukpoe *et al.*, 2014; D'Ans *et al.*, 2018). Some metals also corrode on contact with strongly hygroscopic salts such as $SrBr_2$, which is a further reason material choice feeds directly into reactor design decisions (D'Ans *et al.*, 2018). Embedding the salt in a porous matrix such as expanded graphite improves stability against this failure mode, but at a cost: less salt fits per unit volume, so energy density falls (Clark *et al.*, 2022; Galazutdinova *et al.*, 2024). This trade-off between stability and density recurs throughout the reactor literature and is one reason a single "best" salt or composite has not emerged.

3.2 Reactor Concepts for Solid-Gas Thermochemical Systems

Solid-gas thermochemical reactors are commonly classified according to particle movement—packed (fixed) bed, fluidised bed, or moving bed—and, independently, according to whether the gas comes into direct contact with the reactive salt (open mode) or is separated from it by a heat-exchanger wall (closed mode) (Michel *et*

al., 2014b; Pan and Zhao, 2017; Kur *et al.*, 2023). Table 1 summarises the main characteristics and trade-offs of the three reactor types reported in the literature, while Figure 3 illustrates the corresponding reactor configurations.

3.2.1 Packed-bed reactors

Packed-bed reactors have been widely studied for solid-gas thermochemical energy storage because they are mechanically simple and relatively inexpensive to construct (N'Tsoukpoe *et al.*, 2014; D'Ans *et al.*, 2018). The reactive material remained fixed during both charging and discharging, so operation was inherently batch rather than continuous. As the reaction front moved through the bed, temperature and conversion became non-uniform. Cosquillo Mejia *et al.* (2022) reported that increasing reactor size led to higher pressure drop and greater mass-transfer resistance, making scale-up more difficult. These characteristics limited the suitability of packed-bed reactors for continuous industrial waste-heat upgrading.

3.2.2 Fluidised-bed reactors

In a fluidised bed, salt particles were suspended in an upward gas flow. This promoted effective particle mixing, enhanced heat transfer, and enabled continuous solids handling (Kur *et al.*, 2023; Cosquillo Mejia *et al.*, 2022). Fluidised beds had been adopted in several high-temperature systems based on calcium or metal-oxide reactions (Cosquillo Mejia *et al.*, 2022). These advantages were accompanied by several limitations when salt hydrates were used at lower temperatures. Keeping particles suspended consumed extra energy, particle-particle and particle-wall collisions eroded both particles and reactor surfaces, and stable fluidisation of fine, sticky, moisture-sensitive powders was difficult to sustain (Kur *et al.*, 2023; Esaki *et al.*, 2017; Stengler and Linder, 2020; Cosquillo Mejia *et al.*, 2022). Attrition was a particular problem for salt hydrates, since particles can soften or partially liquefy under locally high humidity. This compounded the deliquescence problem discussed in Section 3.1.2.

3.2.3 Moving-bed reactors

The salt in a moving-bed reactor fell slowly through the reactor under gravity, usually metered by a rotary valve or similar device at the outlet, while gas flowed past it in a parallel, counter-, or crossflow direction (Farcot *et al.*, 2018, 2019; Wyttenbach *et al.*, 2018; Schmidt *et al.*, 2015; Korba *et al.*, 2022). Because particle movement was driven by gravity, moving-bed reactors avoided the auxiliary power demand and particle attrition associated with fluidisation. They also permitted continuous operation while maintaining direct gas-solid contact (Kur *et al.*, 2023; Korba *et al.*, 2022). Crossflow configurations generally performed better than parallel- and counter-flow arrangements (Farcot *et al.*, 2018; Wyttenbach *et al.*, 2018). The shorter gas-flow path reduced pressure drop, limited axial temperature gradients, and produced a more uniform reaction front, allowing greater utilisation of the reactive bed. For this reason, recent studies have favoured the crossflow configuration. Most moving-bed prototypes reported to date use salts such as $CaCl_2$, $Ca(OH)_2$, and $SrBr_2$, with development focused mainly on seasonal heat storage in buildings and other moderate-temperature applications; relatively few studies target industrial waste-heat upgrading above 100 °C (Farcot *et al.*, 2018, 2019; Wyttenbach *et al.*, 2018; Schmidt *et al.*, 2015; Korba *et al.*, 2022). Start-up times were also relatively long: Farcot *et al.* (2018, 2019) reported that their moving-bed reactor required about ten hours to reach steady operation. Such start-up times may be acceptable for seasonal storage systems but could present operational challenges in industrial processes where a faster thermal response is needed. Preisner *et al.* (2020) reported similar behaviour in moving-bed reactors for metal-oxide redox systems, identifying gas-solid heat transfer and channelling as important factors governing reactor performance. These observations suggested that some transport limitations are not unique to salt hydrates.

3.3 Comparing the Three Reactor Types

Packed-bed reactors are mechanically simple and inexpensive but operated batch-wise, limiting their suitability for continuous heat supply. Fluidised-bed reactors provided superior heat and mass transfer but required higher auxiliary energy and were more susceptible to particle attrition. Moving-bed reactors combined continuous operation with lower auxiliary energy demand than fluidised beds, although their performance depended on effective solids handling, control of deliquescence and acceptable start-up behaviour (Kur *et al.*, 2023; Korba *et al.*, 2022; Cosquillo Mejia *et al.*, 2022). Table 1 compares the principal characteristics of the three reactor concepts, while Figure 3 illustrates their basic operating arrangements. The comparison indicated that no single reactor design is ideal for every application. Packed-bed reactors were attractive because of their simplicity, fluidised-bed reactors because of their high heat and mass transfer, whereas

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moving-bed reactors offered a practical balance between continuous operation and auxiliary energy demand. This balance had made moving-bed reactors the focus of recent work on industrial waste-heat upgrading. This explained why recent studies had increasingly focused on crossflow moving-bed reactors for industrial waste-heat upgrading. Sefidgar *et al.* (2026) investigated one such reactor operating in open mode with external salt recirculation during the hydration stage above 100 °C.

Table 1: Comparison of packed-bed, fluidised-bed and moving-bed reactor concepts for solid–gas thermochemical systems.

Criterion	Packed (fixed) bed	Fluidised bed	Moving bed
Continuous operation	No	Yes	Yes
Heat/mass transfer	Poor, uneven reaction front	High, relatively uniform	Moderate to good; crossflow configurations improve temperature uniformity and heat transfer
Parasitic energy use	Low	High (fluidisation, attrition)	Low (gravity-assisted solids transport)
Main limitations	Scale-up, dead zones, pressure drop	Attrition, erosion, complex hydrodynamics	Solids transport, start-up transients, deliquescence control
Representative studies	N'Tsoukpoe *et al.* (2014); D'Ans *et al.* (2018); Cosquillo Mejia *et al.* (2022)	Pan and Zhao (2017); Kur *et al.* (2023); Esaki *et al.* (2017); Stengler and Linder (2020)	Farcot *et al.* (2018, 2019); Wyttenbach *et al.* (2018); Schmidt *et al.* (2015); Korba *et al.* (2022); Sefidgar *et al.* (2026)

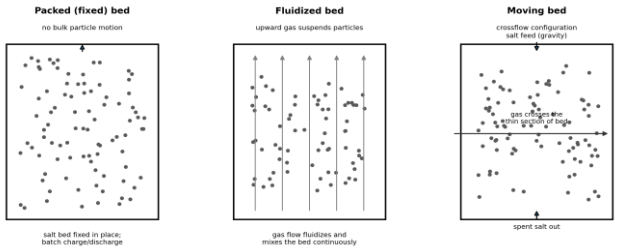

Figure 3: Schematic cross-sections of the packed-bed, fluidised-bed and moving-bed reactor configurations.

3.4 Modelling and Simulation Approaches

3.4.1 Reaction kinetics

The hydration and dehydration kinetics of salt hydrates are commonly represented by the following rate expression (Farcot *et al.*, 2018, 2019; Korba *et al.*, 2022; Sefidgar *et al.*, 2026):

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \quad (1)$$

where $\alpha$is the fraction of material converted, $t$is time (**s**), $k(T)$is the temperature-dependent reaction rate constant (**s^{-1}** for first-order kinetics), and $f(\alpha)$represents the reaction mechanism. The temperature dependence of the reaction rate constant is commonly described by the Arrhenius equation (Korba *et al.*, 2022; Sefidgar *et al.*, 2026):

$$k(T) = A\exp\left(-\frac{E_a}{RT}\right) \quad (2)$$

where $A$is the pre-exponential factor (**s^{-1}**), $E_a$is the activation energy (J mol^{-1}), $R$is the universal gas constant (8.314 J mol^{-1} K^{-1}), and $T$is the absolute temperature (K).

The equilibrium between hydration and dehydration is commonly related to water-vapour pressure through the Clausius–Clapeyron equation (Korba *et al.*, 2022; Sefidgar *et al.*, 2026):

$$\ln P_{eq} = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \quad (3)$$

where $P_{eq}$is the equilibrium vapour pressure (Pa), $\Delta H$is the reaction enthalpy (J mol^{-1}), and $\Delta S$is the reaction entropy (J mol^{-1} K^{-1}).

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Salt-hydrate kinetics are usually described using either particle-scale or reactor-scale models. Particle-scale models, including shrinking-core and nucleation-growth approaches, described how the reaction progressed within individual particles by accounting for nucleation, product-layer growth and diffusion. Reactor-scale models took a different approach. The local reaction rate was related to the difference between the local water-vapour pressure and the equilibrium pressure predicted by the Clausius-Clapeyron relationship, together with the local degree of conversion (Farcot *et al.*, 2018, 2019; Wyttenbach *et al.*, 2018; Korba *et al.*, 2022; Sefidgar *et al.*, 2026).

3.4.2 Coupled reaction–transport modelling of moving-bed reactors

A moving-bed thermochemical heat transformer combined heat transfer, mass transfer and chemical reaction within a continuously moving porous bed. As the reaction proceeded, bed properties such as porosity, permeability, thermal conductivity and density changed with the extent of hydration and dehydration (Korba *et al.*, 2022; Sefidgar *et al.*, 2026). The coupled transport processes are commonly described by the conservation equations for mass and energy:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad 4$$

and

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_r \qquad 5$$

where $\rho$is the density (kg m^{-3}), $u$is the fluid velocity (m s^{-1}), $C_p$is the specific heat capacity (J kg^{-1} K^{-1}), $T$is the temperature (K), $k$is the thermal conductivity (W m^{-1} K^{-1}), and $Q_r$is the volumetric heat released or absorbed by the reaction (W m^{-3}).

Early one-dimensional and reduced-order models established the main characteristics of moving-bed reactor behaviour (Farcot *et al.*, 2018, 2019; Korba *et al.*, 2022). These studies showed that reactor performance was strongly influenced by solid velocity, inlet gas temperature and pressure drop, while providing reasonable agreement with laboratory measurements. Sefidgar *et al.* (2026) later developed a two-dimensional transient CFD model for a continuous crossflow moving-bed reactor using the $SrCl_2/SrCl_2 \cdot H_2O$ system at hydration temperatures above 100 °C. The model was evaluated against an earlier numerical investigation of an $SrCl_2 \cdot H_2O$ moving-bed reactor and experimental measurements obtained from an $SrBr_2$ reactor. Mean absolute percentage errors below approximately 10% were reported for both temperature and conversion, indicating that the model was suitable for design-oriented parametric and sensitivity studies.

Evidence supporting this modelling approach remains limited. The two-dimensional CFD framework had so far been reported by a single research group, and additional validation using independent numerical and experimental studies would strengthen confidence in its wider application. Although the model was evaluated against previously published numerical and experimental datasets, no independent research group had yet reported an experimental study of the same continuous crossflow reactor under comparable industrial operating conditions. The studies of Farcot *et al.* (2018, 2019) and Korba *et al.* (2022) provided the closest independent evidence for moving-bed reactor behaviour, but they examined different reactor configurations and operating conditions. Independent experimental replication of the continuous crossflow reactor had therefore not yet been reported.

3.4.3 Validity and limitations of the local thermal equilibrium assumption

Most moving-bed reactor models assume local thermal equilibrium (LTE), whereby the gas and solid phases are considered to have the same local temperature. This simplified the energy balance by eliminating the need to solve separate energy equations for each phase. Sefidgar *et al.* (2026) examined the validity of this assumption by comparing the characteristic time for gas-solid heat exchange with the characteristic times of reaction and solids transport through the bed. Using estimated heat-transfer coefficients and Nusselt-number correlations, they concluded that heat exchange was sufficiently rapid for the LTE assumption to remain valid under the conditions investigated.

Preisner *et al.* (2020) reported similar findings for a moving-bed thermochemical reactor based on a metal-oxide redox system. Their study also showed that reactor performance was sensitive to the assumed gas-

solid heat-transfer coefficient and to flow channelling, both of which can produce local departures from thermal equilibrium where gas flow becomes non-uniform.

For the moderate reaction rates and particle sizes typically reported for salt-hydrate moving-bed reactors, the local thermal equilibrium (LTE) assumption appears to provide a reasonable approximation (Sefidgar *et al.*, 2026). Its validity is likely to decrease near the reaction front, where reaction rates and temperature gradients are highest and gas-solid temperature differences may become significant. Experimental evidence describing these local non-equilibrium effects in salt-hydrate reactors is still limited, making this an area that requires further investigation.

3.5 Performance Indicators, Sensitivity Analysis, and Optimisation

3.5.1 Key performance indicators

Across the studies reviewed, moving-bed TCHT performance is commonly evaluated using three indicators: steady-state thermal power (often expressed as volumetric power density), the temperature lift achieved by the humid air stream, and outlet solid conversion, which reflected the extent to which the reactive material was utilised before regeneration (Farcot *et al.*, 2018, 2019; Korba *et al.*, 2022; Sefidgar *et al.*, 2026). Improving one performance indicator often affected the others, so reactor design was generally treated as a multi-objective optimisation problem rather than the maximisation of a single parameter (Sefidgar *et al.*, 2026).

3.5.2 Sensitivity analysis

Sefidgar *et al.* (2026) applied a local one-at-a-time (OAT) sensitivity analysis, in which individual input parameters was varied around a reference condition while all others remained unchanged, to evaluate the influence of operating conditions and material properties on reactor performance. Solid velocity and air-side pressure drop were identified as the dominant factors affecting thermal power and outlet conversion, whereas bed thermal conductivity had only a limited influence under the conditions investigated.

This suggested that open-mode reactors operating with humid air were primarily governed by mass transfer. Parameters that influence water-vapour transport therefore had a greater effect on reactor performance than those associated mainly with heat conduction. Preisner *et al.* (2020) reported a similar trend for a moving-bed reactor based on a metal-oxide redox system, providing independent support for the predominance of transport-related parameters. Sefidgar *et al.* (2026) also noted that closed-cycle reactors operating with pure water vapour may exhibit a different sensitivity pattern because heat transfer becomes the dominant limitation. This contrast between open- and closed-mode operation remained relatively unexplored and warrants further investigation.

3.5.3 Optimisation

Sefidgar *et al.* (2026) applied constrained optimisation, using both single- and multi-objective formulations, to identify operating conditions that maximise thermal power while satisfying practical limits on temperature lift and minimum outlet conversion. Derivative-free algorithms such as COBYLA (Constrained Optimisation BY Linear Approximation) were well suited to transient, nonlinear CFD models because they do not require analytical gradients, although they generally involved greater computational effort than gradient-based methods. The optimisation produced an increase of approximately 10% in steady-state thermal power relative to the initial design by jointly adjusting inlet water-vapour content, inlet air temperature and inlet salt conversion, while maintaining the specified operating constraints (Sefidgar *et al.*, 2026). Comparable optimisation studies at the same reactor scale were not identified in the reviewed literature. Consequently, the reported improvement should be regarded as preliminary until confirmed by independent studies.

3.6 Quantitative Benchmarking of Reactor Performance Across the Literature

Direct comparison of reactor performance across published studies was complicated by differences in reactor geometry, working pair, operating conditions and the performance metrics reported. Table 2 summarises representative performance data reported for the principal reactor and system configurations discussed in this review. Open-mode moving-bed reactors operating with humid air have reported steady-state thermal power densities ranging from approximately 1 to 10 kW m^{-3} of bed volume (Sefidgar *et al.*, 2026). Reported volumetric energy densities for salt-hydrate systems covered a much wider range, from roughly 100 to several

hundred kWh m^{-3}, depending on the salt, hydration state and whether the material was used in pure or composite form (Li *et al*., 2022; Spietz *et al*., 2025; Clark *et al*., 2022; Korba *et al*., 2022; Sefidgar *et al*., 2026; Michel *et al*., 2014a). Reported temperature lifts varied from less than 10 K in early seasonal-storage prototypes to more than 40 K in reactors developed for industrial waste-heat upgrading (Farcot *et al*., 2018, 2019; Korba *et al*., 2022; Sefidgar *et al*., 2026).

Table 2: Quantitative performance metrics reported in representative, independently developed salt-hydrate reactor and system studies.

System / Reactor Type	Volumetric Energy Density	Power Density	Operating Conditions	Energy / Exergy Efficiency	Source
Open packed-bed/composite ($SrCl_2$-cement + zeolite 13X, cascade)	108–138 kWh/m³ *(reactor basis)*	Not reported at reactor scale	Dehydration: 50–130 °C; Hydration: 12 °C, 75% RH	Exergy efficiency increased by 6–38% compared with the single-material system	Clark *et al.* (2022)
Open packed-/moving-bed prototype, $SrBr_2/H_2O$, seasonal solar storage	Up to 203 kWh/m³ *(reactor basis)*; up to 388 kWh/m³ *(reactive bed basis)*	0.75–2 W/kg *(salt mass basis)*	Ambient to moderate hydration temperatures	Not reported	Michel *et al.* (2014a)
Continuous crossflow moving-bed, $SrCl_2/SrCl_2 \cdot H_2O$, open mode	Not reported *(volumetric power reported instead)*	~1–10 kW/m³ *(reactor basis)*	Hydration above 100 °C	Not reported	Sefidgar *et al.* (2026)
Pressurisation-assisted THT, various salts, DHW application	Whole-system basis (not directly comparable)	Not reported at reactor scale	Discharge above 65 °C	Energy: 76.3%; Exergy: 89.2%; LEC as low as US$0.115/kWh	Li *et al.* (2024)

Note: Reported values are presented using the basis adopted in the original publications (e.g., reactor volume, reactive bed volume, salt mass or whole-system performance). Because the original studies used different reporting bases, direct normalisation was not possible. The values should therefore be interpreted as indicative comparisons rather than directly equivalent performance metrics.

The studies reviewed indicated that important performance data were still missing for moving-bed TCHTs. Although energy and exergy efficiencies have been reported for packed-bed and system-level configurations (Clark *et al*., 2022; Li *et al*., 2024), comparable second-law performance data were not yet available for the continuous crossflow moving-bed reactor reported by Sefidgar *et al.* (2026). Reported energy densities also differed according to reactor configuration and material selection. Composite packed-bed systems typically reported values of approximately 100–200 kWh m^{-3} (Clark *et al*., 2022), whereas pure-salt systems had achieved up to about 400 kWh m^{-3} when expressed on a reactive-bed basis (Michel *et al*., 2014a). This difference was consistent with the density–stability trade-off discussed in Section 3.1.2.

3.7 Exergy and Second-Law Performance

Most of the reactor-engineering literature reviewed in Sections 3.1–3.6 focused on first-law performance indicators such as thermal power, energy density and outlet conversion. However, second-law analysis had been reported far less frequently, particularly for moving-bed reactors developed for industrial waste-heat upgrading. The exergy efficiency of a thermochemical heat transformer is commonly defined as:

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \quad (6)$$

where Ex_{out} is the useful exergy recovered during heat delivery (J or kJ) and Ex_{in} is the exergy supplied during charging (J or kJ).

Where exergy has been analysed, it revealed differences in thermodynamic performance that first-law metrics alone did not capture. Clark *et al.* (2022) reported that a cascaded $SrCl_2$-cement/zeolite-13X configuration improved exergy efficiency by 6–38% compared with a conventional single-material system, depending on the operating conditions. Similarly, N'Tsoukpoe *et al.* (2016) showed that a cascaded design incorporating internal

condensation heat recovery increased both energy and exergy efficiencies by approximately 1.8 times relative to a conventional single-stage system. At the whole-system level, Li *et al.* (2024) reported energy efficiencies of up to 76.3% and exergy efficiencies of up to 89.2% for a pressurization-assisted, $SrBr_2$-based thermochemical heat transformer producing domestic hot water. Together, these studies indicated that second-law performance was strongly influenced by configuration choices such as cascading, salt selection and pressurisation strategy.

Despite these advances, none of the reactor-scale moving-bed studies reviewed in Sections 3.2–3.6 report an exergy analysis for a continuous crossflow reactor operating above 100 °C. Extending the CFD framework developed by Sefidgar *et al.* (2026) to include a second-law analysis would provide a more complete evaluation of reactor performance. Such an extension should also be supported by validation against published exergy data, including those reported by Clark *et al.* (2022) and Li *et al.* (2024), to establish confidence in the predicted exergy performance.

3.8 Economic Considerations and Technology Readiness

Reactor-scale economic analysis remains limited. Most studies reviewed in Sections 3.1–3.7 concentrate on reactor design, heat and mass transfer, thermal performance and optimisation, while capital cost, operating cost, payback period and levelized cost of heat received much less attention. Among the studies reviewed, only Li *et al.* (2024) presented a quantitative economic assessment, reporting a minimum levelized energy cost of approximately US$0.115 kWh^{-1} for a $LiOH \cdot H_2O$-based thermochemical heat transformer. The analysis was performed for a gigajoule-scale domestic hot-water system rather than an industrial moving-bed reactor, so direct comparison was difficult because the system configuration, auxiliary equipment and operating conditions differed.

Cost was expected to depend on several aspects of reactor design, including the reactor vessel, solids-handling equipment, air distribution and humidification systems. Auxiliary energy for gas circulation, humidification and solids transport was also likely to contribute to operating costs. Material selection introduced another consideration. D'Ans *et al.* (2018) reported severe corrosion of steel and copper exposed to strontium bromide, indicating that corrosion-resistant materials or protective linings may be required. Composite materials improved cycling stability (Clark *et al.*, 2022; Galazutdinova *et al.*, 2024), but this benefit is accompanied by lower energy density. None of the studies reviewed quantified how these factors influence lifetime reactor cost. At present, the economic competitiveness of continuous moving-bed thermochemical reactors cannot be assessed with confidence. Mechanical heat pumps were supported by extensive information on capital cost, operating cost and service life (Rahbari *et al.*, 2025), whereas comparable data for moving-bed thermochemical reactors remained unavailable. Experimental demonstration will therefore be needed before meaningful economic comparisons can be made.

Table 3 summarises the reported stage of development of the reactor concepts reviewed. Most moving-bed reactors remained at the laboratory stage or had only been investigated using validated numerical models. The few pilot-scale systems described in the literature were developed for seasonal thermal energy storage in buildings rather than industrial waste-heat upgrading above 100 °C (Schmidt *et al.*, 2015; Zondag *et al.*, 2013; Kerskes *et al.*, 2012). No published experimental study was identified for the continuous crossflow moving-bed reactor proposed by Sefidgar *et al.* (2026).

Table 3: Technology readiness of the reactor concepts reported in the reviewed literature.

Reactor concept	Reported development stage	Basis for this inference
Packed (fixed) bed, salt hydrate	Lab to small pilot	Long history of laboratory screening and small-scale testing; no large industrial installation identified among the sources reviewed (N'Tsoukpoe *et al.*, 2014; D'Ans *et al.*, 2018)
Fluidised bed, salt hydrate	Lab scale	Reported studies are bench-scale investigations of attrition, erosion and hydrodynamics rather than pilot deployments (Pan and Zhao, 2017; Kur *et al.*, 2023)
Moving bed, seasonal/building-scale	Small pilot plant demonstrated	Named pilot and prototype units reported at building or seasonal-storage scale (Schmidt *et al.*, 2015; Zondag *et al.*, 2013; Kerskes *et al.*, 2012)
Continuous crossflow moving bed, industrial (>100°C)	Simulation-validated model only; no physical demonstration identified	Validated against numerical and experimental datasets, but no dedicated physical pilot rig at this temperature range was found among the sources reviewed (Sefidgar *et al.*, 2026)

The development stages presented in Table 3 were taken from the descriptions provided in the original publications, including validated numerical models, laboratory prototypes and pilot-scale systems. They provided only a relative indication of technology maturity and should not be interpreted as formal Technology Readiness Level (TRL) classifications. Demonstrating the continuous crossflow moving-bed reactor under representative industrial operating conditions remained an important step towards validating reactor performance and establishing its economic viability.

4. Research Gaps and Future Directions

This review identified six research gaps that require further investigation to support the development and industrial deployment of salt-hydrate thermochemical heat transformers. These gaps are summarised in Figure 4 and discussed below.

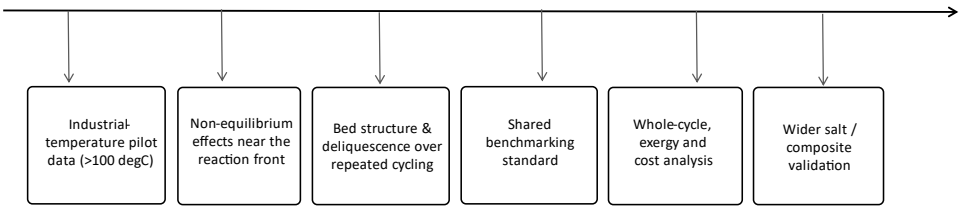

Figure 4: Roadmap of the six research gaps discussed in this section.

Experimental evidence at industrial hydration temperatures remained limited. Most moving-bed investigations had been conducted under conditions relevant to seasonal or building-scale thermal energy storage, whereas experimental studies at the higher hydration temperatures required for industrial process-heat upgrading remained scarce (Farcot *et al.*, 2018, 2019; Wyttenbach *et al.*, 2018; Schmidt *et al.*, 2015; Korba *et al.*, 2022; Sefidgar *et al.*, 2026).

Another important gap concerns long-term structural evolution within the reactive bed. As discussed in Section 3.1.2, repeated hydration and dehydration cycles altered bed porosity and permeability, yet most reactor models continued to assume constant values for these properties. Coupled models linking reaction progress with changes in bed structure remain uncommon (Li *et al.*, 2022; Sefidgar *et al.*, 2026).

A further limitation was the lack of standardised performance reporting. As discussed in Section 3.6, differences in reporting bases made direct comparison between reactor concepts difficult. The adoption of a common reporting framework would improve the consistency and comparability of future studies (Sefidgar *et al.*, 2026; Li *et al.*, 2024).

Current numerical studies also focused predominantly on individual reactor operation, with many simulations restricted to the discharge process. In practice, charging, discharging and heat recovery together determine the overall performance of a thermochemical heat transformer. Integrated modelling of the complete operating cycle, supported by exergy and techno-economic assessment, therefore remained an important area for future research (Sefidgar *et al.*, 2026; Li *et al.*, 2024; Clark *et al.*, 2022).

Reactor optimisation had been reported for only a limited number of reactive materials. Continued development of new salt hydrates and composite formulations raised the question of whether reactor designs optimised for one material remain suitable for others. Extending reactor-scale investigations to a broader range of salts and composite materials would improve the generality of current design recommendations (Li *et al.*, 2022; Spietz *et al.*, 2025; Clark *et al.*, 2022; Galazutdinova *et al.*, 2024). Finally, the review highlighted the need for experimental validation of continuous crossflow moving-bed reactors under representative industrial operating conditions. Such studies are needed to verify model predictions, establish reactor-scale performance, and generate the technical and economic data required for industrial implementation.

5. Conclusion

Salt-hydrate thermochemical heat transformers are attracting increasing interest for industrial waste-heat upgrading because they offer a means of recovering low-grade heat that is otherwise difficult to utilise. The studies reviewed indicated that substantial progress had been made in reactor engineering, particularly in the

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development of continuous moving-bed systems and reactor models based on coupled transport analysis and computational fluid dynamics. By comparison, experimental evidence remained limited. Only a small number of studies had investigated operation at hydration temperatures relevant to industrial waste-heat upgrading, and independent experimental validation of the continuous crossflow moving-bed reactor has not yet been reported. Reactor-scale information on exergy performance, economics and long-term operation is also scarce. Further progress towards industrial application will depend largely on addressing these gaps through experimental demonstration and more comprehensive reactor-scale evaluation.

References

Clark, RJ., Gholamibozanjani, G., Woods, J., Kaur, S., Odukomaiya, A., Al-Hallaj, S. and Farid, M. 2022. Experimental screening of salt hydrates for thermochemical energy storage for building heating application. Journal of Energy Storage, 51: 104415.

Cosquillo Mejia, A., Afflerbach, S., Linder, M. and Schmidt, M. 2022. Development of a moving bed reactor for thermochemical heat storage based on granulated $Ca(OH)_2$. Processes, 10(9): 1680.

D'Ans, P., Courbon, E., Frère, M., Descy, G., Segato, T. and Degrez, M. 2018. Severe corrosion of steel and copper by strontium bromide in thermochemical heat storage reactors. Corrosion Science, 138: 275-283.

Esaki, T., Yasuda, M. and Kobayashi, N. 2017. Experimental evaluation of the heat output/input and coefficient of performance characteristics of a chemical heat pump in the heat upgrading cycle of $CaCl_2$ hydration. Energy Conversion and Management, 150: 365-374.

Farcot, L., Le Pierrès, N., Michel, B., Fourmigué, JF. and Papillon, P. 2018. Numerical investigations of a continuous thermochemical heat storage reactor. Journal of Energy Storage, 20: 109-119.

Farcot, L., Le Pierrès, N. and Fourmigué, JF. 2019. Experimental investigation of a moving-bed heat storage thermochemical reactor with $SrBr_2/H_2O$ couple. Journal of Energy Storage, 26: 101009.

Forman, C., Muritala, IK., Pardemann, R. and Meyer, B. 2016. Estimating the global waste heat potential. Renewable and Sustainable Energy Reviews, 57: 1568-1579.

Galazutdinova, Y., Clark, RJ., Al-Hallaj, S., Kaur, S. and Farid, M. 2024. New thermochemical salt hydrate system for energy storage in buildings. Energies, 17(20): 5228.

Hayatina, I., Auckaili, A. and Farid, M. 2023. Review on salt hydrate thermochemical heat transformer. Energies, 16(12): 4668.

Hua, W., Yan, H., Zhang, X., Xu, X., Zhang, L. and Shi, Y. 2022. Review of salt hydrates-based thermochemical adsorption thermal storage technologies. Journal of Energy Storage, 56: 106158.

Kerskes, H., Mette, B., Bertsch, F., Asenbeck, S. and Drück, H. 2012. Chemical energy storage using reversible solid/gas-reactions (CWS) – results of the research project. In: Proceedings of the 1st International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2012) held in San Francisco, USA, 9 - 11 July 2012. Energy Procedia, 30, 294-304.

Korba, D., Huang, W., Randhir, K., Petrasch, J., Klausner, J., AuYeung, N. and Li, L. 2022. A continuum model for heat and mass transfer in moving-bed reactors for thermochemical energy storage. Applied Energy, 313: 118842.

Kur, A., Darkwa, J., Calautit, J., Boukhanouf, R. and Worrall, M. 2023. Solid-gas thermochemical energy storage materials and reactors for low to high-temperature applications: A concise review. Energies, 16(2): 756.

Li, W., Klemeš, JJ., Wang, Q. and Zeng, M. 2022. Salt hydrate-based gas-solid thermochemical energy storage: Current progress, challenges, and perspectives. Renewable and Sustainable Energy Reviews, 154: 111846.

Li, W., Markides, C.N., Zeng, M. and Peng, J. 2024. 4E evaluations of salt hydrate-based solar thermochemical heat transformer system used for domestic hot water production. Energy, 286: 129602.

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Michel, B., Mazet, N. and Neveu, P. 2014a. Experimental investigation of an innovative thermochemical process operating with a hydrate salt and moist air for thermal storage of solar energy: Global performance. Applied Energy, 129: 177-186.

Michel, B., Neveu, P. and Mazet, N. 2014b. Comparison of closed and open thermochemical processes for long-term thermal energy storage applications. Energy, 72: 702-716.

Miró, L., Gasia, J. and Cabeza, L.F. 2016. Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. Applied Energy, 179: 284-301.

Mukherjee, A., Pujari, A.S., Shinde, S.N., Kashyap, U., Kumar, L., Subramaniam, C. and Saha, S.K. 2022. Performance assessment of open thermochemical energy storage system for seasonal space heating in highly humid environment. Renewable Energy, 201: 204-223.

N'Tsoukpoe, KE., Schmidt, T., Rammelberg, HU., Watts, B.A. and Ruck, WKL. 2014. A systematic multi-step screening of numerous salt hydrates for low temperature thermochemical energy storage. Applied Energy, 124: 1-16.

N'Tsoukpoe, KE., Osterland, T., Opel, O. and Ruck, WKL. 2016. Cascade thermochemical storage with internal condensation heat recovery for better energy and exergy efficiencies. Applied Energy, 181: 562-574.

Pan, ZH. and Zhao, CY. 2017. Gas-solid thermochemical heat storage reactors for high-temperature applications. Energy, 130: 155-173.

Preisner, NC., Bürger, I., Wokon, M. and Linder, M. 2020. Numerical investigations of a counter-current moving bed reactor for thermochemical energy storage at high temperatures. Energies, 13(3): 772.

Rahbari, H.R., Elmegaard, B., Bellos, E., Tzivanidis, C. and Arabkoohsar, A. 2025. Thermochemical technologies for industrial waste heat recovery: A comprehensive review. Renewable and Sustainable Energy Reviews, 215: 115598.

Schmidt, M., Gollsch, M., Grün, M., Giger, F. and Linder, M. 2015. Development of a moving bed pilot plant for thermochemical energy storage with $CaO/Ca(OH)_2$. In: Proceedings of SolarPACES 2015. Proceedings of an international conference held in Cape Town, South Africa, 13 - 16 October 2015.

Sefidgar, Z., Erlandsson, A.C., Huinink, H. and Arabkoohsar, A. 2026. Coupled reaction-transport modeling and optimization of a novel continuous moving-bed thermochemical technology. Applied Thermal Engineering, 303: 132388.

Spietz, T., Fryza, R., Lasek, J. and Zuwała, J. 2025. Thermochemical energy storage based on salt hydrates: A comprehensive review. Energies, 18(10): 2643.

Stengler, J. and Linder, M. 2020. Thermal energy storage combined with a temperature boost: An underestimated feature of thermochemical systems. Applied Energy, 262: 114530.

Wyttenbach, J., Bougard, J., Descy, G., Skrylnyk, O., Courbon,E., Frère, M. and Bruyat, F. 2018. Performances and modelling of a circular moving bed thermochemical reactor for seasonal storage. Applied Energy, 230: 803-815.

Zondag, H., Kikkert, B., Smeding, S., de Boer, R. and Bakker, M. 2013. Prototype thermochemical heat storage with open reactor system. Applied Energy, 109: 360-365.

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