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Thermochemical Energy Storage Using Radial Flow Annular Reactor for Attaining Lower Pressure Drop

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Abstract **-** Thermochemical energy storage (TCES) is gaining attention for seasonal heat storage and space heating applications due to its high thermal energy density and reliable heat retention over a reasonably long period without significant losses. Salt hydrate and moist air-based solid-gas reactive pairs have been proved to be particularly useful for space heating. The auxiliary power required in the form of electrical energy for blowing the air through the packed bed reactor is an important consideration since it depends on various design parameters of the system. A radial flow annular reactor configuration is proposed in the present study. It shows a 65%-80% reduction in the flow work requirement. The parameters, such as the flow direction and flow rate, need to be optimized for better performance and to ensure lesser flow work requirements.

Keywords**:** Thermochemical Energy Storage, Radial Flow, Annular Reactor, Pressure Drop.

1. Introduction

According to the recent International Energy Agency (IEA) reports published in 2021 [1], direct CO_2 emissions attributable to space heating for buildings reached a new peak of 2500 Mt CO_2, with 65% of the heating demand being met by fossil fuels. Buildings account for nearly 30% of global final energy consumption. One of the Sustainable Development Goals (SDGs) of the United Nations, '*access to affordable, reliable, sustainable and modern energy*' (SDG 7), emphasizes increasing the contribution of renewable energy to the global energy mix. In its revised Nationally Determined Contribution (NDC) under Paris Agreement (2021-2030), India decided to reduce the Emissions Intensity of its GDP by 45% by 2030 from the 2005 level [2]. Emission reduction in space heating in the Indian Himalayan Region (IHR), which accounts for 15.6% of land and supports 3.6% of the country's population, can play a crucial role in this pursuit. Shifting to sustainable heating energy sources can reduce the emissions in IHR by 31% by 2030 as compared to business-as-usual (BAU) [3].

Solar energy can be harnessed effectively for space heating if the effects of diurnal and seasonal intermittencies are mitigated. Thermal energy storage methods such as sensible heat storage, latent heat storage, and thermochemical heat storage are effective pathways to reduce the temporal mismatch between the supply and the demand. Particularly for the long-term seasonal heat storage, the high energy density of the storage media and lower losses are desirable. Thermochemical energy storage (TCES) with the energy density of 100-500 kWh/m^3, as against 90 kWh/m^3 and 54 kWh/m^3 for the latent heat and sensible heat storages, respectively, indicates the potential for seasonal heat storage [4]. Thermochemical storages use reversible chemical reactions to store thermal energy in chemical potential, where the energy losses are negligible during dormancy.

Salt hydrates have received considerable attention for TCES owing to the ease of operation offered by them, as well as their deployability in residential applications. Previous studies [5] showed the use of $SrBr_2/H_2O$ based TCES systems for domestic space heating applications. Mukherjee et al. studied the application of $SrBr_2/H_2O$ based TCES numerically for the meteorological conditions of Pune, India [6], and conducted experiments under the conditions prevailing in Mumbai, India [7]. The reversible reaction for Strontium Bromide Hydrate- based TCES system is expressed in equation (1).

$$SrBr_2.6H_2O + Heat \rightarrow SrBr_2.H_2O + 5H_2O \qquad -(1)$$

Operationally, a TCES can either be a closed system or an open system. The open system works with atmospheric air as the working fluid, whereas the closed system involves pure water vapour. Open systems are easier to construct and operate as compared to closed TCES systems [8]. Since the compensation for the pressure drop across the reactor accounts for auxiliary power consumption of up to 3.5% of the thermal power output, there has been a continuous effort to explore configurations that reduce auxiliary power consumption. Previous experimental and numerical studies [9-10] explained the effect of the reactor design on the pressure drop across the TCES reactor bed, and subsequently, the auxiliary power consumption. Mukherjee et al. [11] numerically analyzed the thermal performance by varying the aspect ratio of the reactor bed and the air flow rate through the bed. The parametric analysis indicated that the reactor design affects not only the additional power requirement but the thermal performance of the reactor as well.

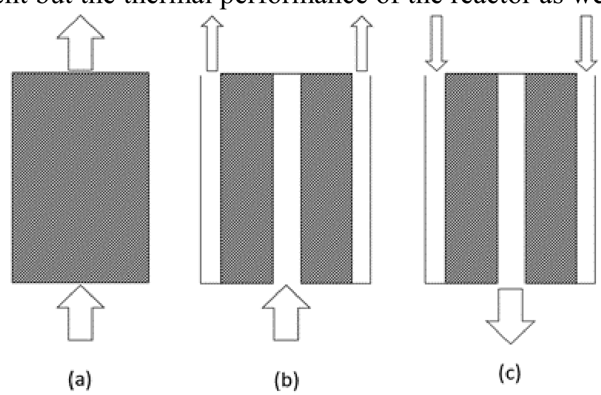

Fig. 1: Reactor configuration (a) Conventional axial flow (b) Radial outward flow (c) Radial inward flow

This study proposes an annular radial flow configuration for the $SrBr_2/H_2O$ based TCES system. Parametric analyses have been performed for the dehydration (charging) process. A numerical model has been developed, and COMSOL Multiphysics® v5.6 [12] is used for the numerical simulations. Amongst the various parameters that influence the performance of the radial flow reactors, only the effect of flow direction is presented in this work. A comparative study presented in this work comprises the conventional cylindrical packed bed reactor with the axial flow, and annular packed bed reactors with two different flow arrangements. Energy efficiency, exergy efficiency, and pressure drop (or additional power requirement) have been used as the reactor performance metrics in the present analysis.

For the proposed numerical model, reaction advancement and flow distribution are verified in two steps: reaction model results are compared against the numerical results available in the literature, and flow distribution results are verified against the analytical calculations. Global reaction advancement and temperature distribution are calculated for a TCES geometry previously proposed by Mukherjee et al. [6], and those are compared with the reported results. Pressure drop is calculated analytically to validate it at four different reaction advancement values (0, 0.25, 0.5, 0.75, and 1.0) for the proposed radial flow annular reactor. The maximum difference between the numerical and the analytical values is about 13% at a reaction advancement value of 0.25, and the difference is about 11% at the start of the reaction for the inward and the outward flow configurations. Three grid sizes available in the simulation tool are used in the grid independence study: coarse (6860 elements), fine (17252 elements), and extremely fine (30249 elements), and the fine grid is used based on the absolute percentage change in the temperature values at the reactor outlet.

Table 1: Geometric, thermal and flow properties of the reactor bed

Parameter (Unit)	Value
Energy Storage (kJ)	3.6×10^{7}
Volume of the Salt Bed (m^3)	0.0258
Volumetric Air Flow Rate (m^3/hr)	15
Porosity of dehydrated bed	0.68
Porosity of hydrated bed	0.38
Permeability of dehydrated bed (m^2)	5.7×10^{-10}
Permeability of hydrated bed (m^2)	5.0×10^{-11}

2. Radial Flow Annular Reactor

Although radial flow reactors are used in several large-scale catalytic reactions in the industry, their usage is limited due due to the complex design. The key design considerations comprise the uniform distribution of the flow along the length of of the reactor and the heat transfer in the void space of the reactor. Based on the directional arrangements of inflow and outflow, there can be two configurations, *viz.* Z- shaped and π-shaped reactors. Based on the flow within the bed, the TCES TCES can be operated as a radially inward flow or an outward flow reactor. As the size of the reactor increases, there is a need to increase the diameter of the axial flow reactors to maintain the same pressure drop, thus limiting the size of the reactor. Radial flow reactors help to reduce the pressure drop across the bed [12]. Radial flow reactors can save up to 64% of the auxiliary power used in blowing air compared to axial flow counterparts.

Figure 1 shows the conventional cylindrical configuration with the axial flow and the Z-shaped annular reactor configuration with suitable inward and outward radial flow directions (for the experimental setup, this indicates air supply and exhaust connections). The proposed $SrBr_2/H_2O$ reactors consider about 39 kg of hydrated salt for storing 10 kWh of thermal energy, with a reactor energy storage density of about 390 kWh/m^3. The salient reactor bed properties are provided in **Table 1.**

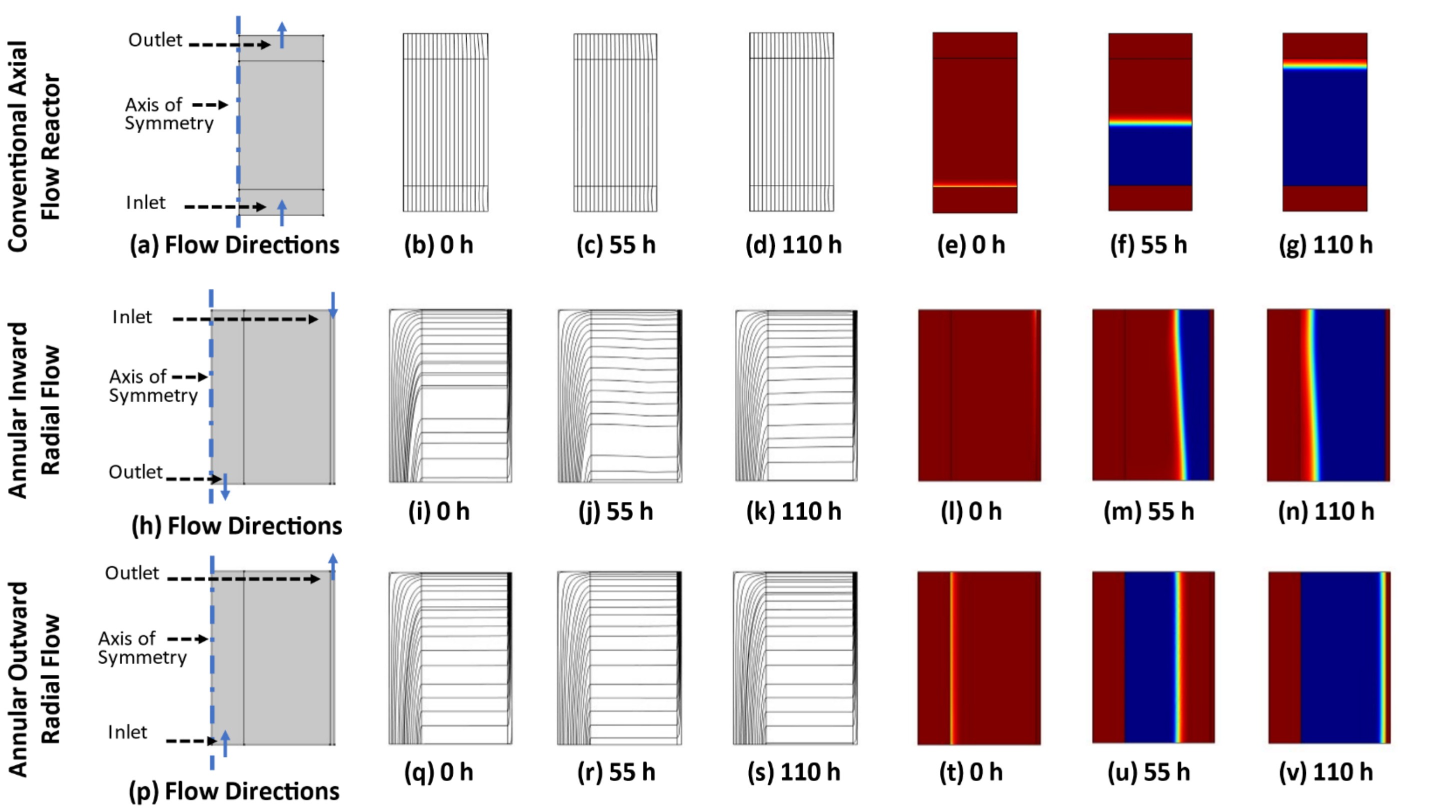

Fig. 2: The Direction of Flow, Flow Distribution, and Reaction Advancement for three different reactor configurations, Conventional Axial Flow **(a-g),** Annular Inward Radial Flow **(h-n),** and Annular Outward Radial Flow **(p-v)**.

3. Flow Distribution and Reaction Front

The effect of the flow distribution within the reactor bed is one of the important concerns in case of the radial flow annual reactors since it has a major impact on the reaction front movement. **Figure 2** shows the flow distribution for the three aforesaid reactor configurations of interest at 0%, 50%, and 100% of the reaction advancement.

In the axial flow reactor, the flow is parallel to the axis of the cylindrical reactor bed **(Figure 2, b-d)**, and a straight unperturbed reaction front moves along the same direction **(Figure 2, e-g)**. The flow distribution for the inward radial reactor is not uniformly distributed along the reactor length, as seen from the streamlines in **Figure 2**. The streamlines more concentrated near the upper end of the vertical reactor bed **(Figure 2, i-k)**. For the outward radial flow **(Figure 2, s)**, the streamlines are more uniformly distributed across the bed length as compared to the inward radial flow case. The excess flow in the upper section for the inward flow configuration is attributed to the higher radial pressure gradient near the hot air inlet.

The reaction front is the boundary between the reacted and unreacted salts at which the actual reaction occurs. It separates high-temperature and low-temperature zones of the reactor bed through positive or negative heat sources at the reaction front through an endothermic or exothermic reaction and is also termed the *heat front*. This boundary effectively separates the unreacted hydrated salt with lesser porosity from the more porous dehydrated salt. This non-uniform porosity distribution further affects the flow distribution, causing nonuniform reaction front advancement. The reaction front, when studied through the lens of flow streamlines (**Figure 2)**, shows that the flow distribution across the bed length affects the reaction advancement in the radial flow reactor. The higher flow rate through the bed near the air flow supply end for the inward radial flow reactor accelerates the movement of the reaction front near the inlet, and causes a protrusion of the reaction front towards the outlet channel (**Figure 2, l-n**). The excess flow near the upper end consumes the whole annular stretch, thereby creating a passage with lesser flow resistance. This creates the non-uniformity of reaction advancement in the reactor bed.

This leads to a reduced global reaction advancement rate towards the end of the charging phase, leading to less utilization of the thermal energy supplied by the hot incoming air, as shown in **Figure 3(a).** This will reduce the pressure drop across the bed, as shown in **Figure 3(b),** and increase the time required for the completion of dehydration (or charging) process.

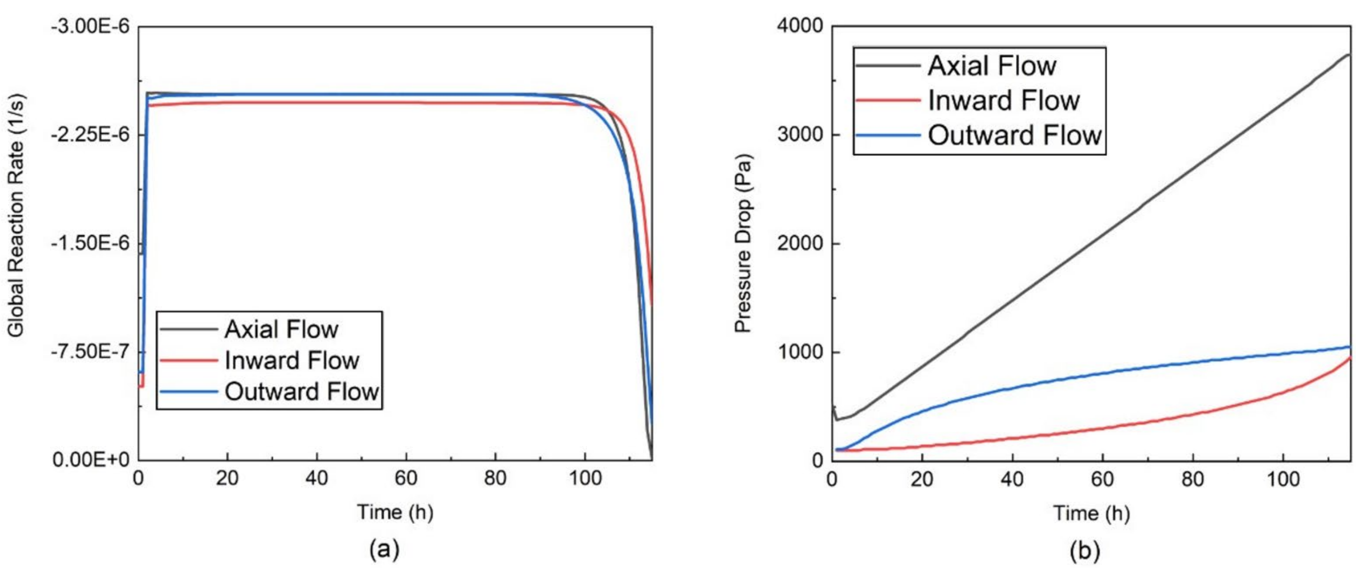

Fig. 3: (a) Global Reaction Rate and **(b)** Pressure Drop across the reactor bed for three configurations for the reactor.

4. Performance of the Charging Process

Table 2 shows the results of the performance analysis of the dehydration (charging) process. The non-uniform movement of the reaction front for radially inward flow in the annular reactor (due to an alternate least resistance path being available for the incoming hot air) reduces the thermal efficiency. Although the alternate path with lesser resistance causes a reduction in the flow power requirement, it causes the reactor to take excess time for complete dehydration of the reactor bed. Analyzing the flow work requirement, the use of a radial flow reactor is justifiable against the axial flow reactor with a nominal compromise on thermal efficiency.

Table 2. Performance of three types of reactor configurations

Flow Type	Axial	Radial Inward	Radial Outward
Thermal energy supplied (kJ)	8.25×10^7	8.47×10^7	8.32×10^7
Thermal energy efficiency (%)	43.65	42.51	43.26
Charging time (hrs)	112	115	113
Average pressure drop (Pa)	2011	436	811
Flow work required (kJ)	3.7×10^6	0.7×10^6	1.3×10^6
Stored energy per unit flow work	10	48	26
Exergy efficiency (%)	59.71	70.82	65.84

4. Conclusions

Although the preliminary results indicate superior thermal efficiency for an axial flow reactor, the exergy efficiency prompts radial inward flow arrangement as a better configuration. A similar study can be conducted for the hydration (or discharging) process to ascertain the overall performance of a complete charging-discharging cycle. Further, the reactor dimensions can be optimized along with the flow directions to realize the best possible system performance under realistic operating conditions. Using an inward radial flow and an outward flow annular reactor will save the flow work requirement by up to 81% and 65%, respectively. This will however lead to a compromise of 2.1% and 0.89%, respectively, in the thermal energy efficiency as compared to the traditional axial flow reactors.

Acknowledgments

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