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1 Performance analysis of a K_2CO_3 -based thermochemical energy storage 2 system using a honeycomb structured heat exchanger

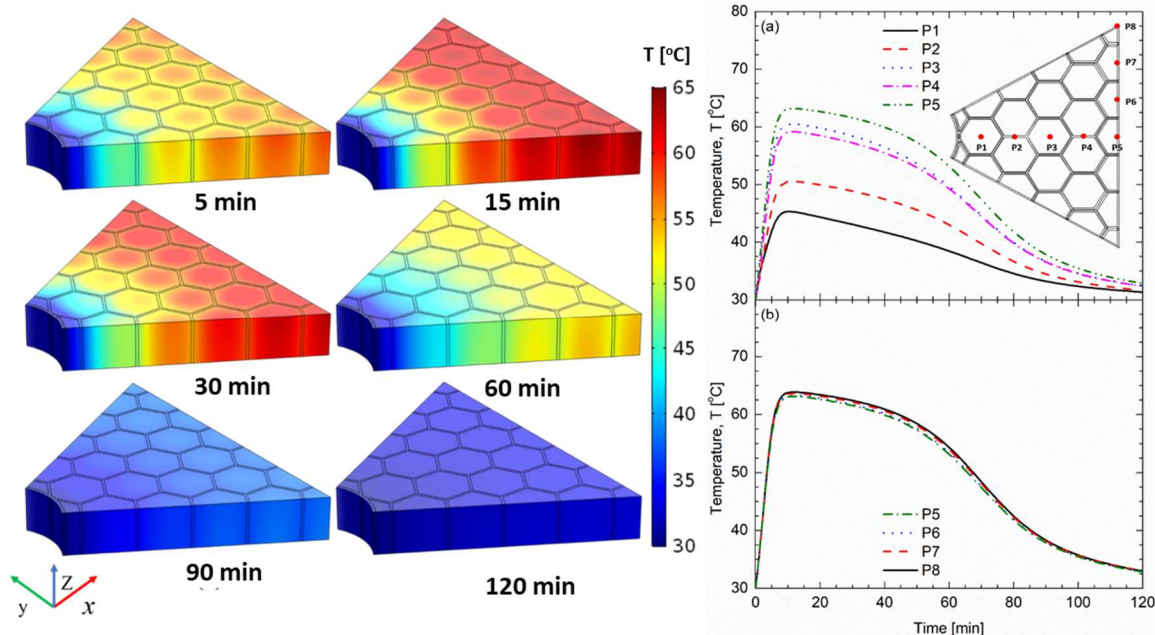
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9 10 Graphical Abstract



11

12 ABSTRACT

13 The application of thermal energy storage using thermochemical heat storage materials is a
14 promising approach to enhance solar energy utilization in the built environment. Potassium
15 carbonate (K_2CO_3) is one of the potential candidate materials to efficiently store thermal
16 energy due to its high heat storage capacity and cost-effectiveness. In the present study, a 3-
17 dimensional numerical model is developed for the exothermic hydration reaction of K_2CO_3 .
18 The heat produced from the reaction is transferred indirectly from the TCM bed through the

19 walls of the honeycomb heat exchanger to a Heat Transfer Fluid (HTF). A parametric study is
20 conducted for varying geometrical parameters of the honeycomb heat exchanger. The
21 obtained results indicate that the reaction rate and heat transport in the TCM bed strongly
22 depends on the geometrical parameters of the heat exchanger. Reducing the cell size of the
23 honeycomb heat exchanger up to a certain level provides better thermal transport as well as
24 improved reaction rate of the TCM bed. The results of this study provide detailed insight into
25 the heat release processes occurring in a fixed bed of K_2CO_3 . The study is useful for
26 designing and optimizing thermo-chemical energy storage modules for the built environment.

27 **Keywords:** Thermochemical; Hydration; Thermal Energy, Reaction; Energy Storage.

28

29 Nomenclature

30	C	<i>concentration [mol]</i>
31	C_p	<i>heat capacity [J/kgK]</i>
32	D_g	<i>water vapor diffusion coefficient [m^2/s]</i>
33	d_p	<i>particle diameter [m]</i>
34	k	<i>thermal conductivity [W/mK]</i>
35	L_C	<i>honeycomb cell length [m]</i>
36	M_v	<i>molar mass of water vapor [kg/mol]</i>
37	p	<i>pressure [Pa]</i>
38	p_{eq}	<i>equilibrium pressure [Pa]</i>
39	R	<i>ideal gas constant [J/mol K]</i>
40	$t_{gap,HTF}$	<i>distance between two HTF tubes [m]</i>
41	T	<i>temperature [$^{\circ}C$]</i>

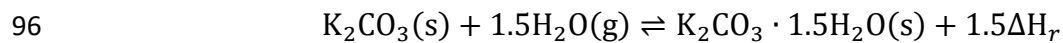
42	u	<i>Darcy velocity [m/s]</i>
43	ε_{eff}	<i>effective bed porosity</i>
44	δ_{fin}	<i>honeycomb fin thickness [m]</i>
45	δ_b	<i>bed height [m]</i>
46	χ	<i>stoichiometric coefficient</i>
47	ρ	<i>density [kg/m³]</i>
48		
49		

50 1. INTRODUCTION

51 Buildings are responsible for approximately 40% of the total energy consumption and for
52 36% of the total CO₂ emissions in the EU, ranking them at the top in terms of energy
53 requirements. [1]. As stated by the European Commission [2], about 75% of the heating and
54 cooling demand is still generated using fossil fuels while only 19% is generated from
55 renewable energy sources. To achieve the EU's climate and energy goals, the heating and
56 cooling sector must sharply reduce its energy consumption and also decrease the usage of
57 fossil fuels. Fossil fuels are not only depleting but are also responsible for global climate
58 change because of their induced rise in greenhouse gas emissions. Therefore, there is an
59 urgent need to focus on renewable energy sources for the heating purposes of buildings. The
60 application of renewable energy sources in the built environment is highly affected by the
61 mismatch between the demand for energy and the supply of energy by renewable resources
62 like solar energy and wind energy. The seasonal mismatch, particularly in the case of energy
63 demand for heating applications, can be resolved up to a large extent by utilizing seasonal
64 heat storage. The main idea is to store thermal energy in summer (high supply, low demand)
65 and utilize it in winter (high demand, low supply). This can be achieved by developing
66 technologies that can efficiently store thermal energy for a longer period with minimal losses.
67 The basic mechanism for developing such technology lies in the property of certain materials
68 that release heat when they ad/absorb water. This mechanism can be utilized to store heat
69 from the sun by using solar heat to dry the material after water is absorbed. The energy stored
70 can be released later by simply adding water vapor to the material.

71 The thermochemical energy storage (TCES) materials as introduced above are promising
72 materials to store thermal energy utilizing a reversible chemical reaction [3–9]. In this
73 reaction, a thermochemical energy storage material (C) absorbs external heat (e.g. solar
74 energy, industrial waste heat) through an endothermic reaction, decomposing into A and B.
75 Products (A and B) are separated by physical means and stored in separate containers. When
76 materials A and B are combined again, an exothermic reverse reaction, generation of C, and
77 release of stored thermal energy occur [10–14]. Although much work has been done in the
78 direction of material characterization, identification, and improvement, as well as process
79 integration and application, little effort has been put into closed thermochemical reactor
80 modelling and process design [15–17]. Funayama et al. [7] suggested the thermal
81 decomposition of calcium hydroxide (Ca(OH)₂) into calcium oxide (CaO) and water vapor as

82 a reversible gas-solid reaction suitable for TCES. The study focused on the development of
83 composite honeycomb support composed of silicon carbide and silicon to enhance the heat
84 transfer in a reaction bed. The results suggest that the heat transfer through the reaction bed
85 was enhanced by the Si-SiC honeycomb support. Zhou et al. [18] developed a numerical
86 model for TCES involving the energy balance and reaction kinetics describing the redox
87 reaction of cobalt oxides (Co_3O_4/CoO pair), to simulate the phenomena of thermochemical
88 storage. Metallic redox pair oxides such as BaO_2/BaO , Mn_2O_3/Mn_3O_4 , CuO/Cu_2O and
89 Fe_2O_3/Fe_3O_4 have been studied for CSP plants [19,20]. Ranjha and Oztekin [21] performed
90 a numerical analysis of a three-dimensional bed with $Ca(OH)_2/CaO$ as the reaction pair. The
91 results of the study provide detailed insight into the heat release processes occurring in a
92 fixed bed of $Ca(OH)_2/CaO$ reaction pair. The study helps designing and optimizing high
93 temperature thermo-chemical energy storage modules for power generation applications. One
94 of the most promising chemical reaction systems for energy storage is the reaction utilising
95 potassium carbonate and water vapor [22]:



97 Gaeini et al. [22] summed up the advantages of a $K_2CO_3 - K_2CO_3 \cdot 1.5H_2O$ system with a
98 storage capacity up to 96.015 kJ/mol (reaction enthalpy of $\Delta H_{r,=}$ 64.01kJ/mol of water)
99 corresponding to a maximum energy density of 1.30 GJ/m³ [23,24]. It features high material
100 energy density and the reaction shows good reversibility. The drawbacks are that
101 thermochemical energy storage materials, in general, have low thermal conductivity. The
102 dehydration and hydration kinetics of the reactions involved are relatively well-identified.

103 This literature assessment indicates that numerical analysis, as well as experimental
104 investigations of the TCES reactive materials and reactor design, has attracted considerable
105 interest during the past few decades. Although sensible and latent heat storage systems have
106 made their way into commercial applications, TCES (currently at the laboratory stage, mainly
107 due to technical challenges) could be applied in many applications [20,25,26]. Therefore,
108 numerical simulation tools to model the thermochemical reactions, understand the reaction
109 kinetics, and optimize the system performance, are very essential. In the recent past, bionics
110 based tools have been realized to be one of the advanced tools, especially in the field of fluid
111 flow and heat transfer applications including chemical reactors [27], biomedical equipment
112 [28,29], and electronic cooling [30–34]. The fin structures made by natural assortment

113 encourage the improvement of the TCES device. By realizing natural structures, the fins with
114 bionic structures, for instance, tree-shaped fins [34,35], Koch fractal fins [36], and
115 snowflake-shaped fins [37,38], have been proposed by researchers for their enhanced heat
116 transport, subsequently increasing the thermal transport effectiveness of TCES devices. With
117 the existence of honeycomb meshed structures in nature, the idea surfaced to solve the
118 problem of thermal transport in a TCES device with the use of such a structure as a reactor
119 bed. Therefore, the present work focuses on the performance analysis of TCES based on
120 potassium carbonate (K_2CO_3) filled in a honeycomb heat exchanger structure.

121 The performance analysis has been achieved by studying heat and mass transfer through the
122 reactive bed of $K_2CO_3 \cdot 1.5H_2O$ designed for a thermochemical heat storage system. The
123 numerical model developed for the purpose has been solved using COMSOL Multiphysics
124 software [39]. The study is performed to see the impact of the honeycomb heat exchanger on
125 the recovery of the thermo-chemically-stored energy as well as the reaction rate in the TCM
126 bed. Further, a parametric study has been conducted to investigate the effect of various
127 honeycomb heat exchanger design parameters (i.e. honeycomb cell size [L_c], honeycomb fin
128 thickness [δ_{fin}], bed height [δ_b] and distance (denoted with subscript *gap*) in between two
129 HTF tube [$t_{gap,HTF}$]) on the temperature variation, the reaction advancement and the
130 recovery of the thermo-chemically-stored energy. These parameters are highly related to the
131 heat exchanger design of the honeycomb structure. It is explicitly noted here that the material
132 properties of potassium carbonate are considered to be constant during the reaction and that
133 resulting effects like swelling/shrinking are not taken into account.

134 The work performed as presented in this article is organized in the following manner. Firstly,
135 in the introduction section, the general background and the aim of this work are presented.
136 After the introduction, the numerical model as developed in the present work is discussed
137 including the mathematical formulation of the heat and mass transport equations employed in
138 the TCM bed, the computational procedure, and the model validation. Further, the results of
139 the numerical simulations and a parametric study for the hydration of the TCM bed are
140 analyzed. Finally, a summary along with the key conclusions of the present work is presented
141 in the last section.

142 2. GEOMETRY AND MODEL IMPLEMENTATION

143 The working pair of the material considered in the present study is potassium carbonate and
144 water vapor. Olives and Mauran [40] showed that heat transfer in TCM bed through thermal
145 radiation can be ignored as the working temperature of the thermochemical heat storage
146 system considered here is in the range of 10 °C to 90 °C only. They further showed that, for a
147 system with water vapor, the prevailing heat transfer mode is conduction. Heat transfer by
148 convection in the porous medium can also be neglected as the reaction between the potassium
149 carbonate and the water vapor is supposed to be instantaneous and gets completed so fast that
150 there is no temperature difference between the salt and the water vapor and single
151 temperature equations can be used for the macroscopic description of the heat transfer
152 processes in the porous medium. The vapor transport in the TCM can be of Knudsen, Darcy,
153 or inertial flow type since it depends on vapor pressure and velocity at the porous media
154 boundaries. The fluid is considered to flow through the TCM bed consisting of approximately
155 spherical particles with global porosity. Water vapor is considered an ideal gas, due to its low
156 concentration and partial pressure. A relatively low permeability value of the porous bed
157 (Table 1) makes it possible to model mass transfer with Darcy's law. The sensible heat of the
158 reactive bed is also taken into account in the energy balance considering the sensible heat of
159 water vapor and the stored heat in the salt as one entity. We also assume that the thermal
160 conductivity and heat capacity of the salt are constants. The thermo-physical properties of
161 potassium carbonate, water vapor, and operating parameters that have been used in the model
162 are given in Table 1. The following assumptions have been made in the present study: (i) the
163 properties of the phases are isotropic and uniform. Unless specified otherwise the physical
164 and chemical properties of the constituents are assumed to be constant; (ii) the water vapor is
165 in thermal equilibrium with the solid phase; (iii) The porous medium is not deformable; (iv)
166 The gaseous adsorbate adheres to the ideal gas law; (v) The effects of pressure work and
167 viscous dissipation are negligible.

Table 1. The thermophysical properties of TCM and operating parameters considered in the present study [22,41]

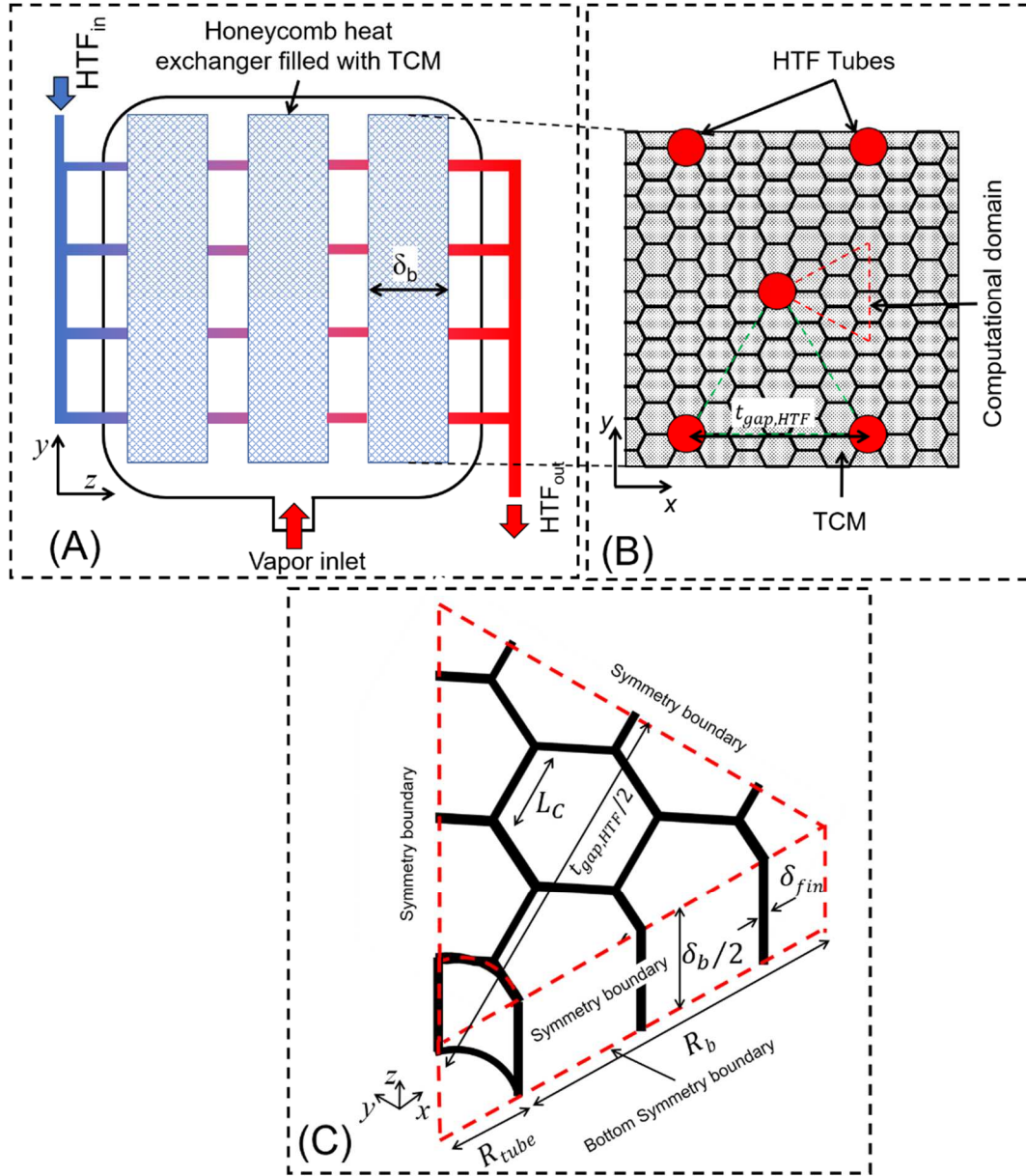
Name	Value	Description
d_p	$0.5 \times 10^{-3} m$	particle diameter
ϵ_{eff}	0.4	effective bed porosity
D_v	$10^{-9} m^2/s$	water vapor diffusion coefficient
$C_{p,v}$	1864 J/kgK	heat capacity of water vapor

$C_{p,s}$	830 J/kg K	heat capacity of solid potassium carbonate
$C_{p,fin}$	900 J/kg K	heat capacity of fin material
ρ_s	2210 kg/m ³	the density of potassium carbonate
ρ_{fin}	2700 kg/m ³	density of fin
k_{eff}	0.44 W/m K	thermal conductivity of potassium carbonate
k_{fin}	238 W/m K	thermal conductivity of fin
E_a	46.22 kJ/mol	activation energy
M_v	0.01802 kg/mol	the molar mass of water vapor
M_s	0.138 kg/mol	the molar mass of K_2CO_3
χ	1.5	stoichiometric coefficient
ΔH_r	64.01 kJ/mol	reaction enthalpy kJ/mol of water
R	8.314 J/mol K	ideal gas constant
A_f	3.0838×10^6 1/min	pre-exponential factor in reaction kinetics
T_i	30°C	initial temperature
T_{eva}	15°C	evaporator temperature
T_{HTF}	30°C	cooling temperature of HTF
p_i	425 Pa	initial pressure
C_i	0.07 mol/m ³	initial concentration

168 The schematic of the honeycomb heat exchanger thermochemical reactor bed considered in
169 the present study is illustrated in Fig. 1A. The system consists of several honeycomb heat
170 exchanger beds filled with K_2CO_3 particles and separated at a distance to allow water vapor
171 to reach the TCM material. The thickness of each honeycomb heat exchanger bed is indicated
172 with δ_b . The heat transfer fluid (HTF) tubes are connected in the center to each heat
173 exchanger unit in the system. The whole system is enclosed in a chamber where water vapor
174 is injected from the evaporator and relatively cold water is flowing in the HTF tubes. An
175 expanded side view of one honeycomb heat exchanger is presented in Fig. 1B, where
176 hexagonal cells are connected to HTF tubes and the distance between two HTF tubes is given
177 by $t_{gap,HTF}$. Further, the HTF tubes are arranged in such a way that they make a hexagonal
178 pattern themselves. Because of the hexagonal pattern of the HTF tube distribution in each
179 honeycomb heat exchanger bed, symmetry can be considered in the heat and mass transport
180 processes. Due to this symmetry in heat and mass transport, a small element of the reactor

181 bed is considered in the present study (red dashed line in Fig. 1B). A three dimensional
182 schematic of the computational domain is presented in Fig. 1C, where L_C is one edge of the
183 hexagonal cell, δ_{fin} is the thickness of the hexagonal cell wall and R_{tube} is the radius of the
184 HTF tube. The height of the computational domain is considered as half of the bed height
185 because of the presence of symmetry in the heat and mass transfer at the center of each
186 honeycomb heat exchanger bed as water vapor is transported from both sides of the bed. It is
187 noted here with reference to Fig. 1C that the numerical simulations are carried out in a
188 Cartesian coordinate system x , y and z because the system is not exactly cylindrical.
189 However, the x -coordinate more or less corresponds to the radial position and the y -
190 coordinate to the tangential position.

191 In the present study, the radius of the HTF tube is constant for all the cases and its value is
192 taken 0.02 m. It is also assumed that the temperature gradient in the HTF flow direction is
193 very small and can be neglected. The temperature at the internal surface of the HTF tube is
194 set equal to the inlet temperature of HTF and its value is 30 °C. The inlet of water vapor is
195 considered at the top of the computational domain and the symmetry boundary at the bottom
196 of the computational domain. At the top of the computational domain, the water vapor arrives
197 with a fixed vapor concentration of 0.71 mol/m^3 . This value is obtained based on water
198 vapor properties as it is assumed that vapor is an ideal gas (hence we applied the gas law
199 formula $\rho_v = M_v C$). The vacuum in the whole system is created at a pressure of around 1708
200 Pa. At $t = 0$, the concentration in the TCM bed equals 0.07 mol/m^3 and the initial temperature
201 is set to 30 °C.



202

203

204

205

Fig. 1 Schematic of the geometry of the TCM bed and computational domain (a) TCM energy storage system, (b) side view of honeycomb heat exchanger filled with TCM, (c) computational domain.

206

3. GOVERNING EQUATIONS

207

3.1 VAPOR TRANSPORT IN POROUS MEDIUM

208

The vapor transport in the TCM filled in the honeycomb cells is governed by the mass conservation equation of the reactive gas and can be written as [42]:

210

$$\varepsilon_{eff} \frac{\partial c}{\partial t} - \nabla \cdot (D_v \nabla C) + \nabla \cdot (\mathbf{u}C) - R_c = 0 \quad (1)$$

211 where C and D_v are the concentration and the diffusion coefficient of the water vapor,
 212 respectively. ε_{eff} is the effective porosity and its value is taken 0.4 in the present study [41].
 213 The last term (R_C) in eq. (1) is the reaction term which will be discussed in the reaction
 214 kinetics section. The vapor transport in the porous medium occurs not only from diffusion but
 215 also from advection, where a difference in pressure causes the bulk motion of the gas. This
 216 leads to a viscous flow and therefore the vapor transport in the porous medium is governed by
 217 Darcy's law considering the acceleration due to gravity. The Darcy velocity \mathbf{u} in the porous
 218 medium is given by:

$$219 \quad \mathbf{u} = -\frac{\kappa}{\mu}(\nabla p - \rho_v \vec{g}) \quad (2)$$

220 where ρ_v is water vapor density and g is universal gravitational constant. The p is the gas
 221 pressure and given by gas law ($p = CRT$, where C is the molar concentration, R is the
 222 universal gas constant and T is the temperature). The permeability κ of the porous medium
 223 can be obtained from the semi-empirical Blake–Kozeny equation as:

$$224 \quad \kappa = \frac{d_p^2 \varepsilon_{eff}^2}{150(1-\varepsilon_{eff})^2} \quad (3)$$

225 where d_p is the particle diameter and ε_{eff} is the bed porosity. The Sutherland law or the
 226 viscosity-temperature relation is often used to determine the dynamic viscosity μ in the range
 227 of -156 [°C] to 1787 [°C], where the ratio S/T_{ref} is empirically taken as 0.505 [43].

$$228 \quad \mu = \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{\frac{1}{2}} \left\{ \frac{1 + \frac{S}{T_{ref}}}{1 + \frac{S}{T_{ref}}} \right\} \quad (4)$$

229 with T_{ref} and μ_{ref} as reference temperature and viscosity respectively.

230 3.2. HEAT TRANSFER IN POROUS MEDIUM

231 For the phases existing in the reactor bed, the macroscopic description of heat transfer in a
 232 porous medium is often investigated by the use of a single temperature equation. Here, local
 233 thermal equilibrium is referring to the fact that the macroscopic temperatures of the three
 234 phases (liquid water in the salt, water vapour in the reactive gas and the solid salt itself) are
 235 close enough such that a single temperature description of the heat transport processes can be

236 used. Duval et al. [44] added that the assumption of local thermal equilibrium was acceptable
 237 in many cases of unsaturated porous media with liquid–vapour phase change, particularly for
 238 most thermal decomposition processes. Therefore the heat transfer in the porous
 239 thermochemical bed is governed by the heat transfer diffusion equation, which can be written
 240 as [42]:

$$241 \quad (\rho C_p)_{eff} \frac{\partial T}{\partial t} + \rho_v C_{p,v} \mathbf{u} \cdot \nabla T - k_{eff} \nabla^2 T = Q \quad (5)$$

242 where $(\rho C_p)_{eff}$ is the effective volumetric heat capacity, k_{eff} is the effective thermal
 243 conductivity and its value is considered 0.4 W/mK in the present study [41]. The Q is the
 244 heat generated due to the reaction of water vapour with K_2CO_3 and its value depends on the
 245 reaction term R_c and will be discussed in the reaction kinetics section. The effective
 246 volumetric heat capacity $(\rho C_p)_{eff}$ is calculated by the following equation:

$$247 \quad (\rho C_p)_{eff} = \rho_v C_{p,v} \varepsilon_{eff} + \rho_s C_{p,s} (1 - \varepsilon_{eff}) \quad (6)$$

248 3.3. HEAT TRANSFER IN FIN

249 The heat transfer in the fin can be calculated with the heat transfer diffusion equation [45]:

$$250 \quad \rho_{fin} C_{p,fin} \frac{\partial T}{\partial t} - k_{fin} \nabla^2 T = 0 \quad (7)$$

251 where ρ_{fin} , $C_{p,fin}$ and k_{fin} is the fin density, heat capacity and thermal conductivity
 252 respectively.

253 3.4. REACTION KINETICS

254 Solving the intra-particle mass balance equations is often time-consuming. To avoid this
 255 problem, in practice often a lumped approach is followed as an approximation, which has
 256 proven to be physically consistent [14,46]. The reaction term in equation (1) is calculated,
 257 using the reaction advancement:

$$258 \quad R_c = \chi \frac{\rho_s}{M_s} (1 - \varepsilon_{eff}) \frac{\partial \alpha}{\partial t} \quad (8)$$

259 where ρ_s is the density of the solid TCM, χ is the Stoichiometric coefficient, M_s is the
 260 molecular weight of potassium carbonate and α is the reaction advancement. Since reaction
 261 kinetics deals with measurement and parameterization of the process rates, the rate can be
 262 parameterized using three major variables: the temperature T , the chemical conversion α and
 263 the vapor pressure p . Systematic studies have been performed about the different expressions
 264 of the kinetic rates [15] in heterogeneous kinetics and the global form of that rate can be
 265 presented as follows:

$$266 \quad \frac{\partial \alpha}{\partial t} = k(T)f(\alpha)h(p) \quad (9)$$

267 The value of the conversion α in time-dependence reflects typically the progress of the
 268 overall transformation of a reactant to products, meaning the advancement of the reaction. Lu
 269 et al. [47] (1996), Mazet et al. [48] had shown that the pressure dependence for reversible
 270 solid-gas synthesis can be expressed as:

$$271 \quad h(p) = 1 - \left(\frac{p_{eq}}{p}\right) \quad (10)$$

272 where p and p_{eq} are the partial and equilibrium pressures of the gas product respectively
 273 (here the water vapour). The value of equilibrium vapour pressure p_{eq} [Pa] is given by [22]:

$$274 \quad p_{eq} = 4.228 \times 10^{12} \exp\left(-\frac{7337}{T}\right) \quad (11)$$

275 where T is the temperature in K . The ratio between equilibrium water vapor pressure (p_{eq})
 276 and water vapour pressure (p) called the pressure ratio $\left(\frac{p_{eq}}{p}\right)$, is an important parameter in
 277 reaction kinetics. Assuming that mass transfer and chemical reaction are sufficiently rapid so
 278 that equilibrium values of concentrations always exist at prevailing temperature, the equation
 279 linking the equilibrium pressure to the temperature for the decomposition is given by the
 280 Clausius-Clapeyron relationship. For this type of reaction, several authors [5,47,48] have
 281 shown that the reaction rate can be presented as follows:

$$282 \quad \frac{\partial \alpha}{\partial t} = A_f \exp\left(-\frac{E_a}{RT}\right) (1 - \alpha)^{2/3} \left(1 - \frac{p_{eq}}{p}\right) \quad (12)$$

283 where A_f is the pre-exponential Arrhenius factor taking into account the kinetic effect, E_a the
284 Arrhenius activation energy. The source term Q in the eq. (8) is the heat generated or
285 consumed in adsorber bed which is given by:

$$286 \qquad \qquad \qquad Q = R_c \Delta H_r \qquad \qquad \qquad (20)$$

287 where R_c is the reaction rate as introduced previously and ΔH_r is the reaction enthalpy (given
288 in table 1).

289 3.5. INITIAL AND BOUNDARY CONDITIONS

290 The following boundary conditions are prescribed, see Fig. 1C:

- 291 • At the top of the computational domain, the water vapour pressure is fixed.
- 292 • At the bottom of the computational domain, the symmetry boundary condition is applied,
293 for temperature and gas flux.
- 294 • At the surface of the honeycomb heat exchanger, the velocity field is zero ($-n\nabla u = 0$),
295 there are heat continuity between porous TCM and honeycomb fin, therefore
296 ($-nk_{eff}\nabla T = -nk_{fin}\nabla T$).
- 297 • At the HTF tube inner surface, a constant temperature boundary condition is applied ($T =$
298 T_{HTF}).
- 299 • At the periphery (other than the HTF boundary) of the computational domain, the
300 symmetry boundary condition is applied.

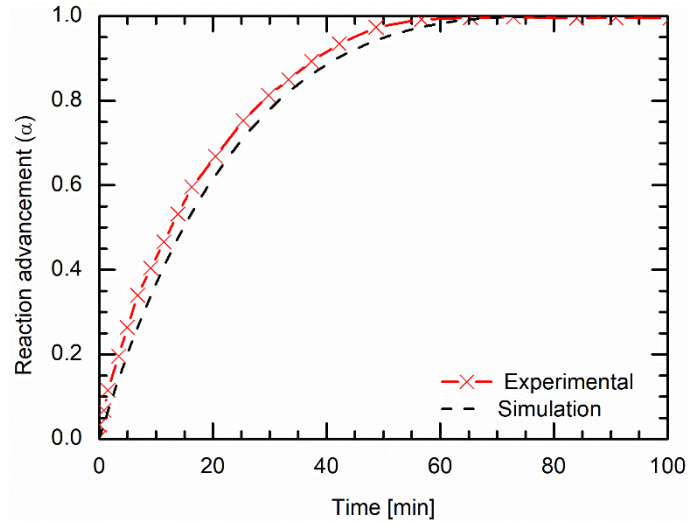
301 Initially, the temperature of the computational domain was ($T_i = 30^\circ C$) and the reaction
302 advancement of the bed is fixed at zero ($\alpha = 0$). The initial pressure is fixed at 425 Pa
303 corresponding initial water vapor concentration is $0.07 \text{ mol}/\text{m}^3$.

304 3.6. COMPUTATIONAL PROCEDURE AND MODEL VALIDATION

305 The governing partial differential equations subjected to initial and boundary conditions are
306 simultaneously solved using the commercial package of COMSOL Multiphysics 5.3a, which
307 is based on the Finite Element Method (FEM). The expressions for the thermophysical
308 properties of TCM and reaction kinetics are programmed in COMSOL through user-defined
309 functions. The partial differential equations for heat and mass transport are programmed in
310 the ‘heat transfer in porous media’ and ‘transport of diluted species in porous media’

311 interfaces available in COMSOL [49]. With respect to the 3-dimensional model for the heat
312 and mass transport study, free meshing with tetrahedral elements is used to create the overall
313 mesh. The numerical simulation model is divided into two calculation domains i.e. the solid
314 and the porous domain and each discretized using the Galerkin method. The mesh size and
315 time step dependencies of the solutions are studied to check the accuracy of the numerical
316 results and computation time. It was optimized with three progressive decreasing mesh sizes
317 and final values are taken because further reducing mesh size did not significantly affect the
318 final results. The mesh size was decreased near the interfaces of the solid with the porous
319 medium to reduce the error in the calculations. The maximum and minimum mesh element
320 size considered in the present study is 0.0013 m and 0.000132 m which is small enough to
321 obtain accurate mesh independent solutions. An independent discretization of the time
322 domain is applied using the method of lines and time-stepping algorithms automatically
323 switch between explicit and implicit steps depending on the problem. The time step may vary
324 in order and step length depending on the evolution of the solution with time. The maximum
325 time step is defined as 1 min, however, at the initial stage of convergence, the time step is
326 taken very small by the solver, in the order of 10^{-3} seconds.

327 The numerical model for heat and mass transport in the porous medium as used in the present
328 study is based on a model developed in our lab for the hydration of silica gel. First, the
329 kinetics of silica gel is replaced with the kinetics of potassium carbonate, and then the heat
330 transfer model for the honeycomb heat exchanger is added. The developed model for the
331 reaction kinetics is validated with experimental results presented by Gaeini et al. [22] in
332 terms of reaction advancement, see Fig. 2. In the experiments, the hydration isotherm is kept
333 at 30 °C and hydration starts only when water vapor is introduced to the system while the
334 isotherm temperature is maintained. The water vapor pressure was maintained at 1715 Pa.
335 More details can be found in Gaeini et al. [22]. The comparative results present the validity of
336 the developed model as results from the present study are in good agreement with the
337 experimental results obtained by Gaeini et al. [22]. However, a minor shift compared to the
338 experimental data is observed. This can be explained by a possible difference in some
339 thermo-physical properties (effective thermal conductivity and effective porosity) of the
340 porous K_2CO_3 sample as these values are not presented by Gaeini et al. [22]. In the present
341 work, these properties are taken from the literature [41].



342

343 Fig. 2 Comparison of reaction advancement with experimental study of Gaeini et al. [22]

344 **4. RESULTS AND DISCUSSION**

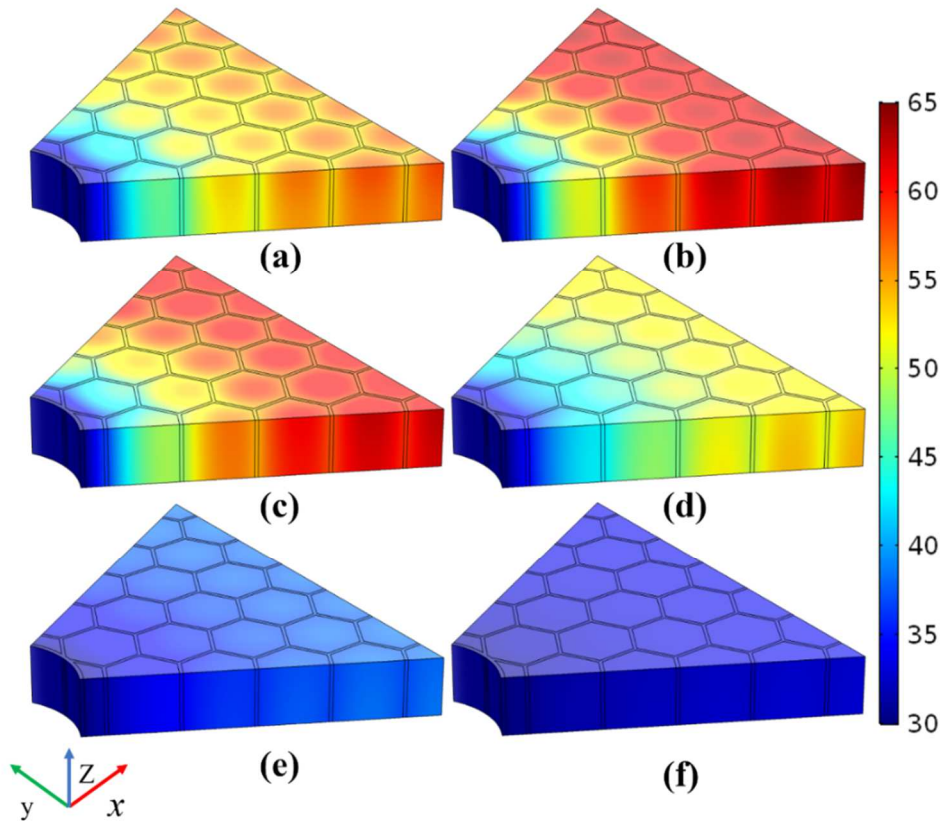
345 The present study is conducted for the hydration of K_2CO_3 and the obtained results of the
 346 study are presented in two subsections. The initial and boundary conditions considered in the
 347 present study are listed in Table 1 and section 3.5. In the first subsection the heat transfer,
 348 reaction advancement and reaction rate are being discussed. In the second subsection, the
 349 results of the parametric study for different cell sizes (L_c), bed heights (δ_b), fin thickness
 350 (δ_{fin}) and the distance between two HTF tubes ($t_{HTF,gap}$) are discussed.

351 **4.1. HEAT TRANSFER, REACTION ADVANCEMENT AND REACTION RATE**

352 Figure 3 presents the temperature contour of the computational domain (i.e. TCM bed with
 353 honeycomb heat exchanger) at 5 min, 15 min, 30 min, 60 min, 90 min and 120 min
 354 considering $L_c = 0.01\text{ m}$, $\delta_b/2 = 0.015\text{ m}$, $\delta_{fin} = 0.001\text{ m}$ and $t_{gap,HTF}/2 = 0.090\text{ m}$.

355 For the given configuration, the actual volume of the porous K_2CO_3 sample is 52.43 cm^3 and
 356 the ratio of the porous bed to fin volume is 3.6. From Figure 3, it can be observed that the
 357 temperature in the computational domain for each time span is increasing with an increase in
 358 the distance from the HTF tube and also increases towards the center of each hexagonal cell
 359 of the honeycomb heat exchanger. Further, the temperature is higher at the top of the
 360 computational domain and starts decreasing with an increase in the distance from the top of
 361 the bed as the concentration of the water vapour is progressively decreasing with an increase
 362 in the distance which results in a reduced heat generation in the bed. The temperature

363 distribution in each hexagonal cell is not perfectly symmetric; its maximum value is slightly
 364 shifted away from the HTF tube. The temperature distribution in the y-direction of the bed
 365 (comparable to the tangential direction in cylindrical coordinates) is almost periodic because
 366 of symmetry in the hexagonal fin structure of the honeycomb.



367

368 Fig.3 Colour contour of the temperature of TCM bed at different time levels (a) 5 min, (b) 15
 369 min, (c) 30 min, (d) 60 min, (e) 90 min, (f) 120 min

370 Further, the temperature variations with time at different probe points in the computational
 371 domain are shown in Fig. 4. The probe points P1 to P5 are equally spaced at a distance of
 372 0.02 m in the x-direction (radial direction) starting from the HTF tube and P5 to P8 are
 373 positioned at the center of each hexagonal cell and also space at an equal distance of 0.01732
 374 m in the y-direction (tangential direction) from probe point P5. Further, all the probe points
 375 are positioned at the half-thickness of the computational domain ($z = \delta_b/4$).

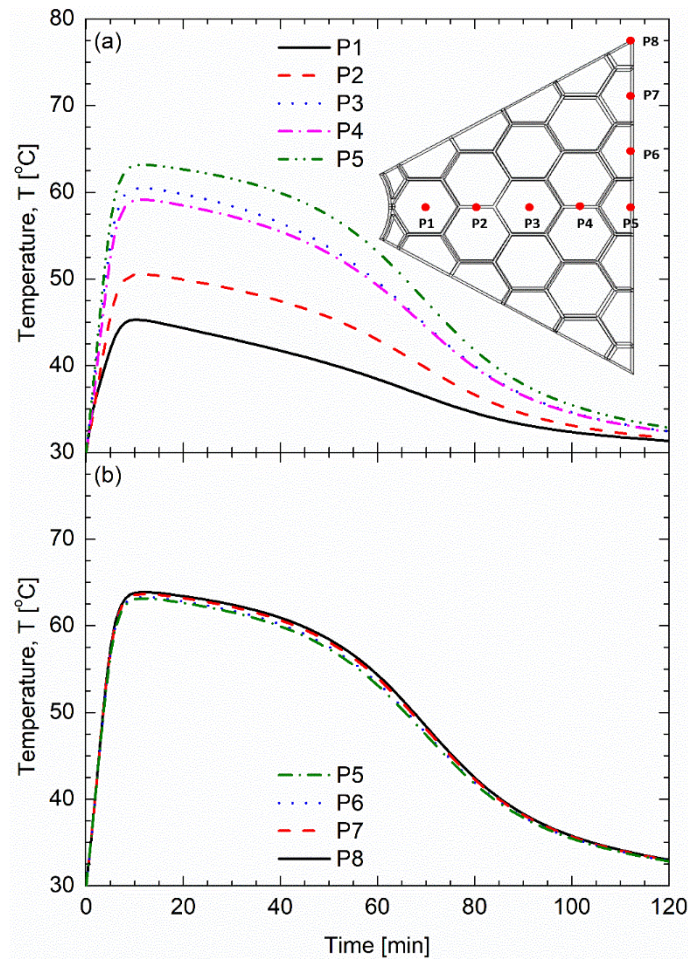
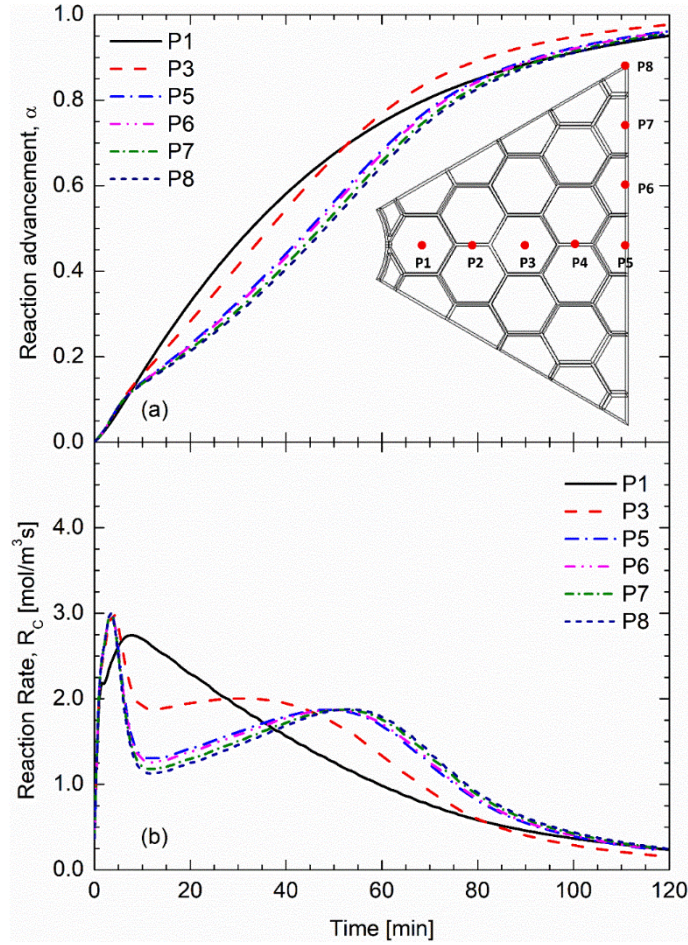


Fig. 4 Temperature variation at the different probe points (a) in the x-direction (radial direction), (b) in the y-direction (tangential direction)

Fig. 4 shows the honeycomb heat exchanger bed temperature variation at the above-discussed probe points (i.e. P1 to P8). The temperature of the bed at all probe points is increasing sharply at the initial stage of reaction and reaches its maximum value at around 10 min, further it starts decreasing gradually. Fig. 4(a) represents the variation of bed temperature with time at probe point P1 to P5. The minimum temperature is observed at probe point P1 as it is nearest to the HTF tube. The temperature of the bed is increasing with an increase in distance from the HTF tube, though, the temperature at probe point 4 is lower than P3 as P4 is positioned in the honeycomb fin and P3 is placed in the center of the hexagonal cell. Fig 4(b) represents the variation of temperature at different probe points (P5 to P8) in the y-direction (tangential direction). The temperature difference in probe points P5 to P8 is very small because of the presence of the honeycomb fin structure and symmetry considerations.

Fig 5 presents the variation of reaction advancement (α , eq. (12)) and reaction rate (R_c , Eq. (8)) of water vapor with K_2CO_3 at different probe points with time. The positions of probe

393 points are presented above. Because the probe points P2 and P4 coincide with the fin
394 structure, they are left out of this analysis. Up to 55 min, the reaction advancement is the
395 highest at probe point P1, from 55 min onwards probe point P3 shows the highest reaction
396 advancement, as shown in Fig. 5(a). Minimum reaction advancement is obtained at probe
397 point P8 because it is the furthest probe point from the HTF tube in the thermochemical
398 reactor bed. The decreasing order of reaction advancement at different probe points before
399 and after 55 min is $P1 > P3 > P5 > P6 > P7 > P8$ and $P3 > P1 > P5 > P6 > P7 > P8$ respectively. It should
400 be noted however that the values for reaction advancement are quite close to each other for
401 the points P5-P8 over the full-time interval. This applies to all points for times greater than 80
402 min. Besides, the reaction rate of water vapour with K_2CO_3 at the different probe, points are
403 shown in Fig. 5(b). Initially, the reaction rate increases sharply and reaches its maximum
404 value for all probe points and then it starts decreasing with different proportions. At probe
405 point P1, the reaction rate continuously decreases after getting its maximum value, though,
406 for other probe points, the reaction rate sharply decreases with time until reaches its
407 minimum value ($\approx t = 10$ min). After reaching the minimum value of reaction rate it further
408 starts increasing with time up to ≈ 35 min for P3 and $t = \approx 55$ min for P5, P6, P7, P8. This can
409 be explained as the water vapour seeps into the bed and reacts with TCM, which results in the
410 temperature rise in the bed. The temperature rise in the bed causes a reduction in the reaction
411 rate.



412
413 Fig. 5 Variation of (a) reaction advancement, (b) Reaction rate at the different
414 probe points with time

415 4.2. PARAMETRIC STUDY

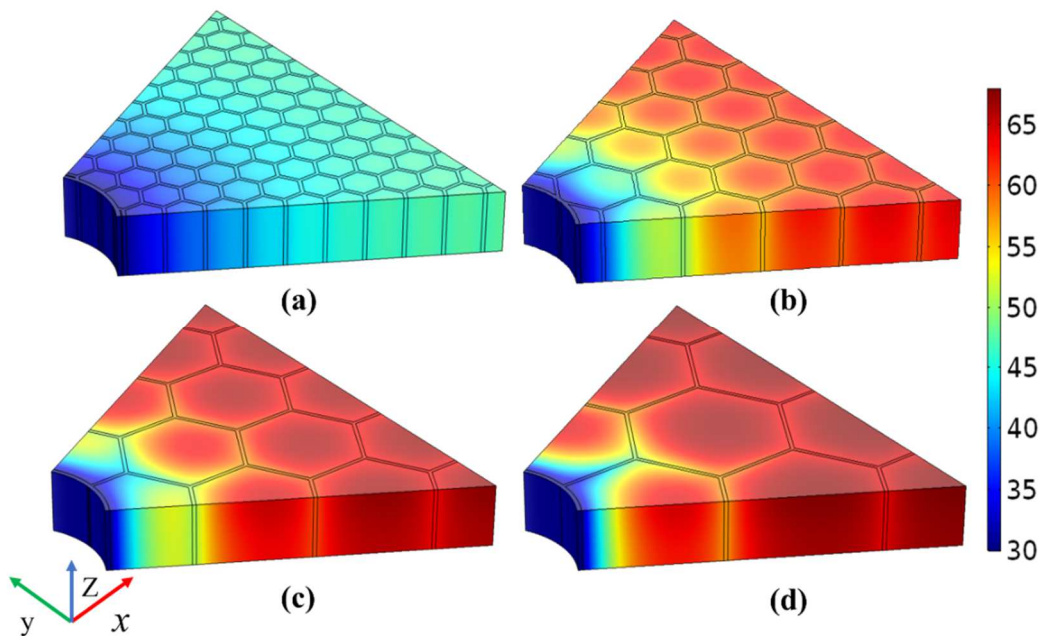
416 Below a discussion on the results obtained from a parametric study of honeycomb cell size,
417 bed height, honeycomb fin thickness and the distance between two HTF tubes are presented.
418 The results are presented in terms of temperature variation (T), reaction advancement (α) and
419 power output (P_o). The power output P_o is obtained by integrating the heat flux over the HTF
420 tube surface and is defined as:

421
$$P_o = \iint \vec{q} dS$$

422 with the heat flux \vec{q} integrated over the surface S of the HTF tube.

423 4.2.1. Effect of honeycomb cell size

424 Fig. 6 shows the temperature contours of the computational domain for four different
 425 honeycomb cell sizes i.e. $L_C = 0.005$ m, 0.01 m, 0.015 m, and 0.02 m at 15 min. The default
 426 values of $\delta_b/2$, δ_{fin} and $t_{gap,HTF}/2$ for all the cell sizes are 0.015 m, 0.001 m, and 0.09
 427 respectively. The volumes of the porous K_2CO_3 samples for $L_C = 0.005$ m, 0.01 m, 0.015 m,
 428 and 0.02 m are 52.43 cm^3 , 59.49 cm^3 , 61.95 cm^3 and 63.20 cm^3 respectively. Further, the
 429 volume ratios of the porous K_2CO_3 samples with respect to the metallic fin volumes are 3.6,
 430 7.9, 12.25 and 16.57 respectively. The smaller honeycomb cell size increases the number of
 431 cells in the TCM bed and consequently also increases the fin material volume. The increment
 432 of the fin volume in the computational domain causes enhanced heat transport in the bed;
 433 however, it reduced the actual heat capacity of the bed. The temperature gradient in the
 434 computational domain is lowest for the smallest cell size of the honeycomb structure and vice
 435 versa, because of better heat transport from the TCM bed to the HTF.



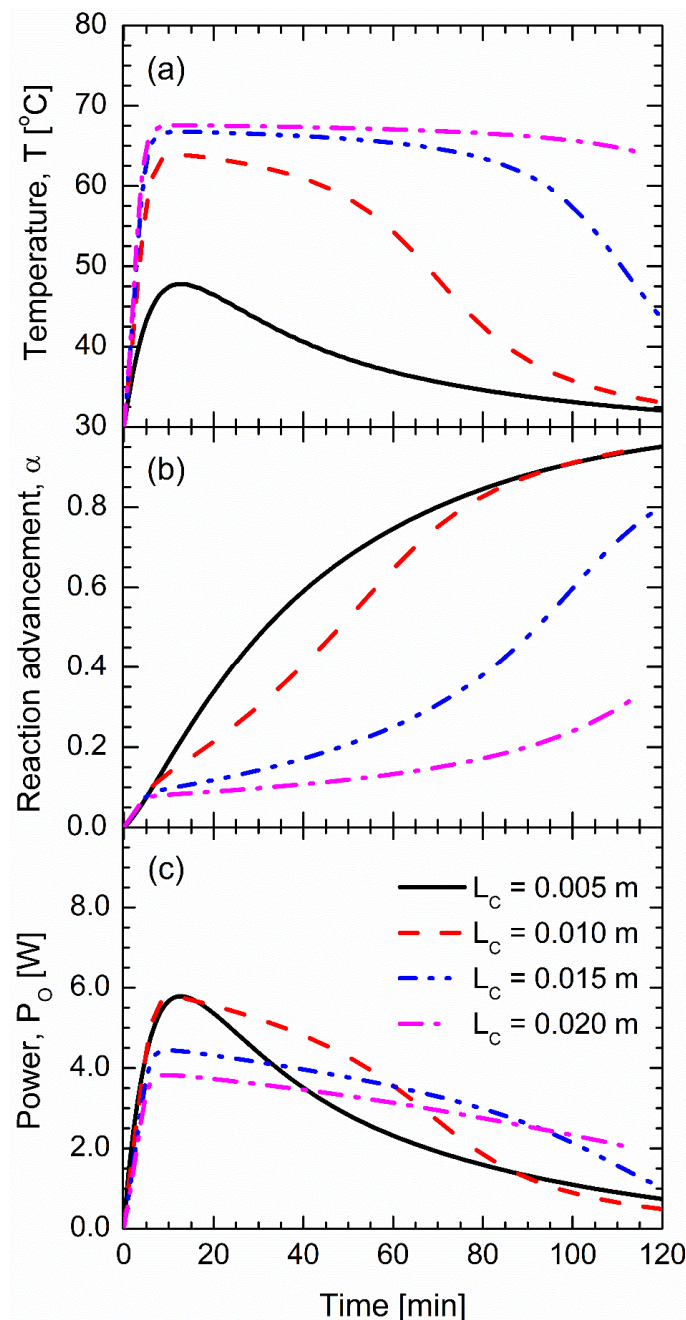
436

437 Fig. 6 Temperature contours at different cell sizes (a) $L_C = 0.005$ m, (b) $L_C = 0.01$ m, (c) $L_C =$
 438 0.015 m, (d) $L_C = 0.02$ m at 15 min

439

440 Further, the temperature variation, reaction advancement and thermal power transported to
 441 the HTF with time are plotted in Fig. 7 at probe point 8 (as shown in fig 5a). The temperature
 442 at probe point P8 (the point furthest away from the HTF tube) increases sharply for all the

443 cell sizes and gradually starts decreasing after reaching its maximum value as shown in Fig
 444 7(a). For the lowest cell size ($L_C = 0.005$ m), the maximum temperature at probe point P8
 445 reaches 47°C after 10 min. Further, the temperature gradually starts decreasing and reaches
 446 the lowest value of 32°C at 120 min. For $L_C = 0.01$ m, the temperature at probe point P8
 447 sharply reaches its maximum value and starts decreasing gradually until 60 min. Further, it
 448 sharply decreases and becomes 32°C after 120 min. Fig. 7(b) shows the reaction
 449 advancement at probe point P8 for all cell sizes. For $L_C = 0.005$ m and $L_C = 0.01$ m, the
 450 reaction advancement at 120 min reaches around 0.95 however for $L_C = 0.015$ m and $L_C =$
 451 0.02 m its value is 0.8 and 0.35 respectively.



452

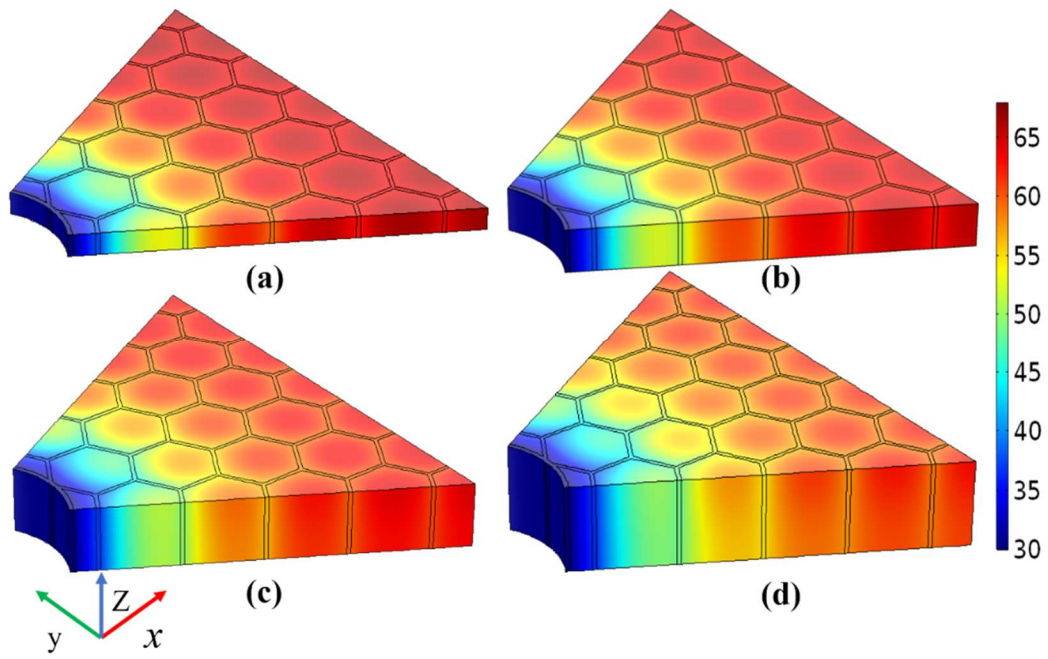
453 Fig. 7 Variation of (a) Temperature, (b) reaction advancement and (c) power output with time
454 for different cell sizes; temperature and reaction advancement are presented for probe point
455 P8

456 The lowest reaction advancement is obtained with the highest cell size because of the higher
457 temperature which causes a reduced reaction rate of water vapour with K_2CO_3 . Fig. 7 (c)
458 presents the variation of power output with time at the HTF tube surface in the computational
459 domain. The power output (P_O) reaches its maximum value at the same time when the
460 temperature at probe point P8 is maximum. For $L_C = 0.015$ m and $L_C = 0.02$ m, there is a
461 gradual reduction in power output after reaching its maximum value, however, it is sharper
462 for $L_C = 0.005$ m and $L_C = 0.01$ m. The smaller honeycomb cell size leads to a higher number
463 of cells in the computational domain which reduces the actual volume of the reacting material
464 in the computational domain. The reduction in the volume of reacting material reduces the
465 heat storage capacity of the reacting bed.

466 4.2.2. Effect of bed height

467 The temperature contours of the computational domain for four different bed height ($\delta_b/2 =$
468 0.005 m, $\delta_b/2 = 0.01$ m, $\delta_b/2 = 0.015$ m, and $\delta_b/2 = 0.02$ m) at 15 min are presented in
469 Fig. 8. The fin thickness, honeycomb cell size and the distance between two HTF tubes are
470 considered 0.001 m, 0.01m and 0.09 m respectively. The volumes of the porous K_2CO_3
471 samples for $\delta_b/2 = 0.005$ m, $\delta_b/2 = 0.01$ m, $\delta_b/2 = 0.015$ m, and $\delta_b/2 = 0.02$ m are
472 19.83 cm^3 , 39.66 cm^3 , 59.49 cm^3 and 79.32 cm^3 respectively. The ratio of the porous
473 K_2CO_3 sample volume to the metallic fin volume is fixed at 7.9. At 15 min, the temperature
474 gradient in the computational domain is almost the same for all bed heights (Fig. 8 (a)-(d)),
475 however, its value is slightly higher for the computational domain with the lowest bed height
476 as compared to the higher bed height (Fig. 9). For the smaller bed height, the water vapour
477 easily seeps into the bed and reacts with the TCM, which enhances the reaction rate and
478 results in a higher temperature.

479

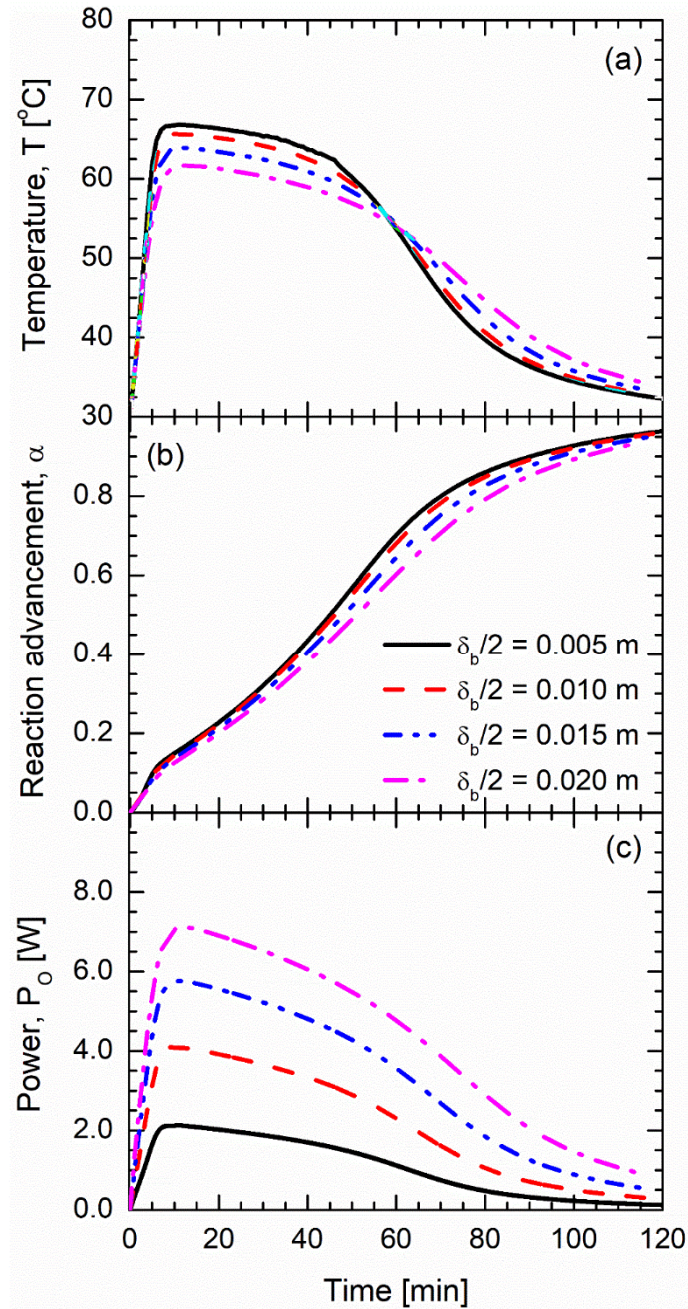


480

481 Fig. 8 Temperature contours at different bed height (a) $\delta_b/2 = 0.005 m$, (b) $\delta_b/2 = 0.01 m$,

482

(c) $\delta_b/2 = 0.015 m$, (d) $\delta_b/2 = 0.02 m$ at $t=15 \text{ min}$



483

484 Fig. 9 Variation of (a) Temperature, (b) reaction advancement and (c) power output with time
 485 for different cell sizes; temperature and reaction advancement are presented for probe point

486

P8

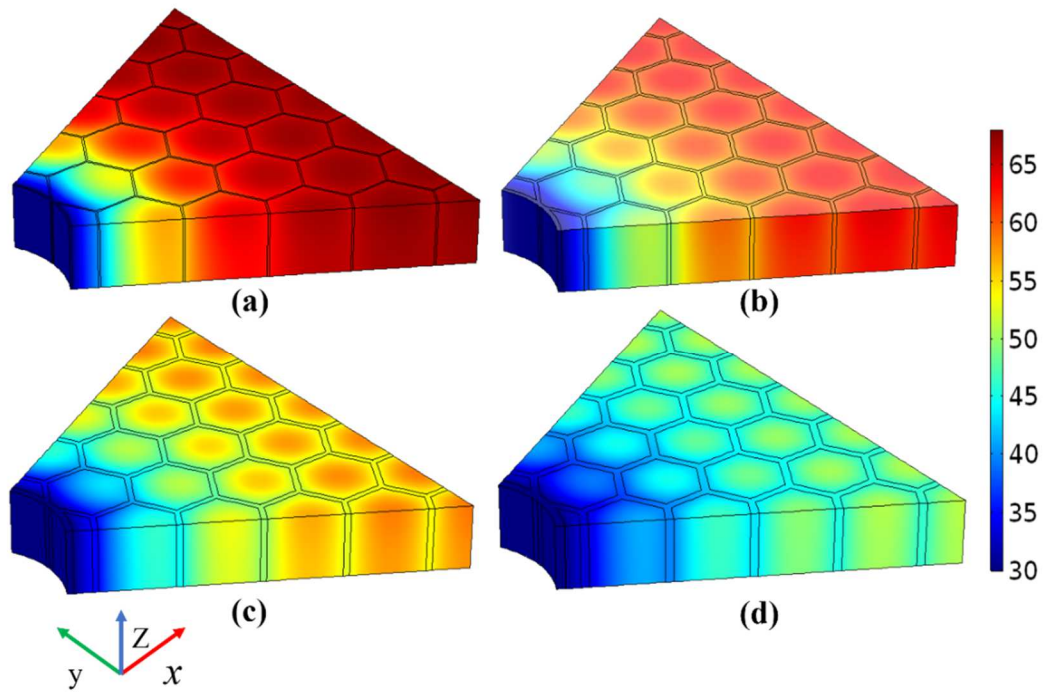
487 The temperature at probe point P8 (discussed in the previous section) is presented in Fig 9 (a)
 488 for different bed thicknesses. At this probe point the bed temperature is higher for the lowest
 489 bed thickness until $t = 60$ min and vice versa after 60 min. Further, reaction advancement is
 490 always higher for the lowest bed height (i.e. $\delta_b/2 = 0.005$ m) because of the lower flow
 491 resistance and lower uptake of vapor in the bed which results in better accessibility of and
 492 higher concentration in the computational domain. Further, the power output from the

493 computational domain to the HTF surface is presented in Fig. 9(c). The maximum power is
494 obtained with the maximum bed thickness simply because of the presence of more TCM in
495 the computational domain. However, it is interesting to see that the power output is linearly
496 increasing with the bed height for the 2 smaller values ($\delta_b/2 = 0.005\text{ m}$ and $\delta_b/2 =$
497 0.01 m) but slightly decreases for the 2 larger values ($\delta_b/2 = 0.015\text{ m}$ and $\delta_b/2 = 0.02\text{ m}$).
498 There is a progressive attenuation in power with time for higher bed height because the
499 fraction of hydrated TCM increases and subsequently reduce the reactant volume with time,
500 which results in lower power production.

501

502 4.2.3. Effect of honeycomb fin thickness

503 The temperature variation of the computational domain for four different fin thicknesses
504 ($\delta_{fin} = 0.0005\text{ m}$, $\delta_{fin} = 0.001\text{ m}$, $\delta_{fin} = 0.0015\text{ m}$, and $\delta_{fin} = 0.002\text{ m}$) at 15 min are
505 presented in Fig. 10 considering $L_c = 0.01\text{ m}$, $\delta_b/2 = 0.015\text{ m}$ and $T_{gap,HTF}/2 = 0.09\text{ m}$.
506 The volumes of the porous K₂CO₃ samples for $\delta_{fin} = 0.0005\text{ m}$, $\delta_{fin} = 0.001\text{ m}$, $\delta_{fin} =$
507 0.0015 m , and $\delta_{fin} = 0.002\text{ m}$ are 63.19 cm^3 , 59.49 cm^3 , 55.90 cm^3 and 52.43 cm^3
508 respectively. Further, the ratios of the porous K₂CO₃ sample volumes to the metallic fin
509 volumes are 16.57, 7.92, 5.03 and 3.60 respectively. The highest temperature gradient in the
510 TCM bed is observed with the lowest fin thickness due to the reduction in the thermal
511 transport from the bed to the HTF surface (increased heat resistance because of a reduced
512 cross-sectional area of the fin structure). Further, the increment in the fin thickness also
513 reduces the actual volume of the TCM in the bed, which also results in reduced heat
514 generation and causes a lower bed temperature.

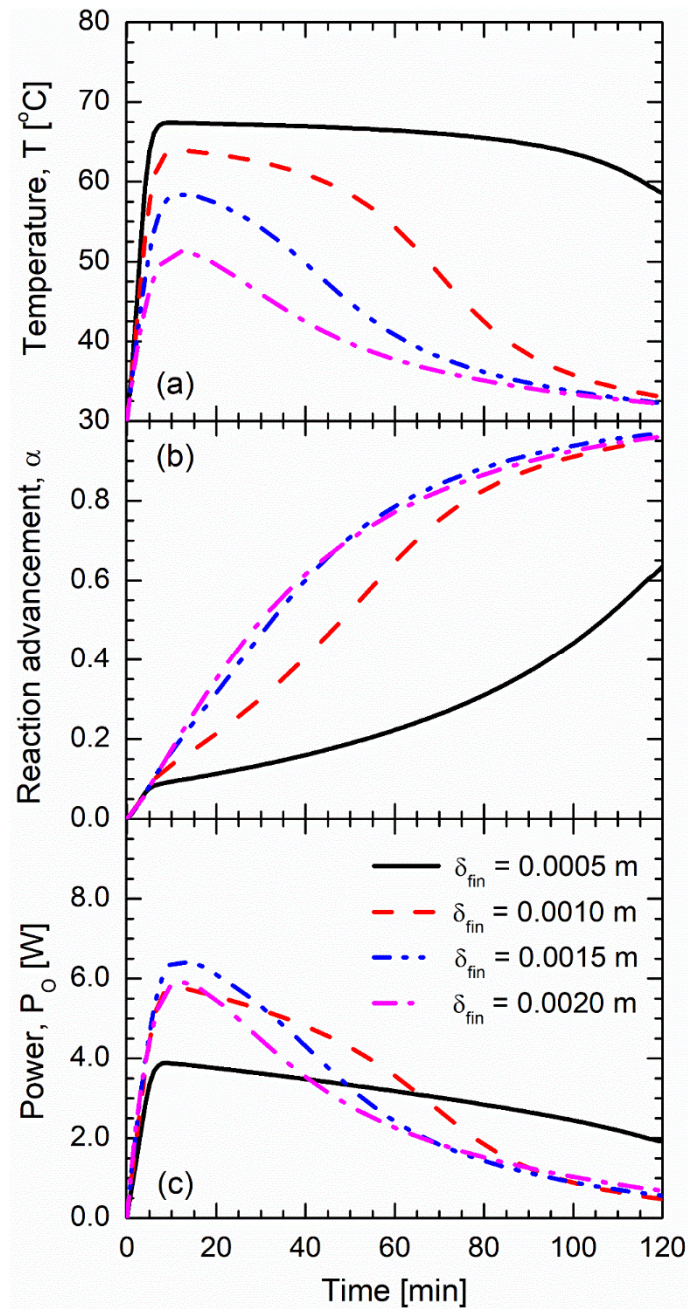


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516 Fig. 10 Temperature contours at different honeycomb fin thickness (a) $\delta_{fin} = 0.0005$ m, (b)

517

$\delta_{fin} = 0.001$ m, (c) $\delta_{fin} = 0.0015$ m, (d) $\delta_{fin} = 0.002$ m at $t=15$ min



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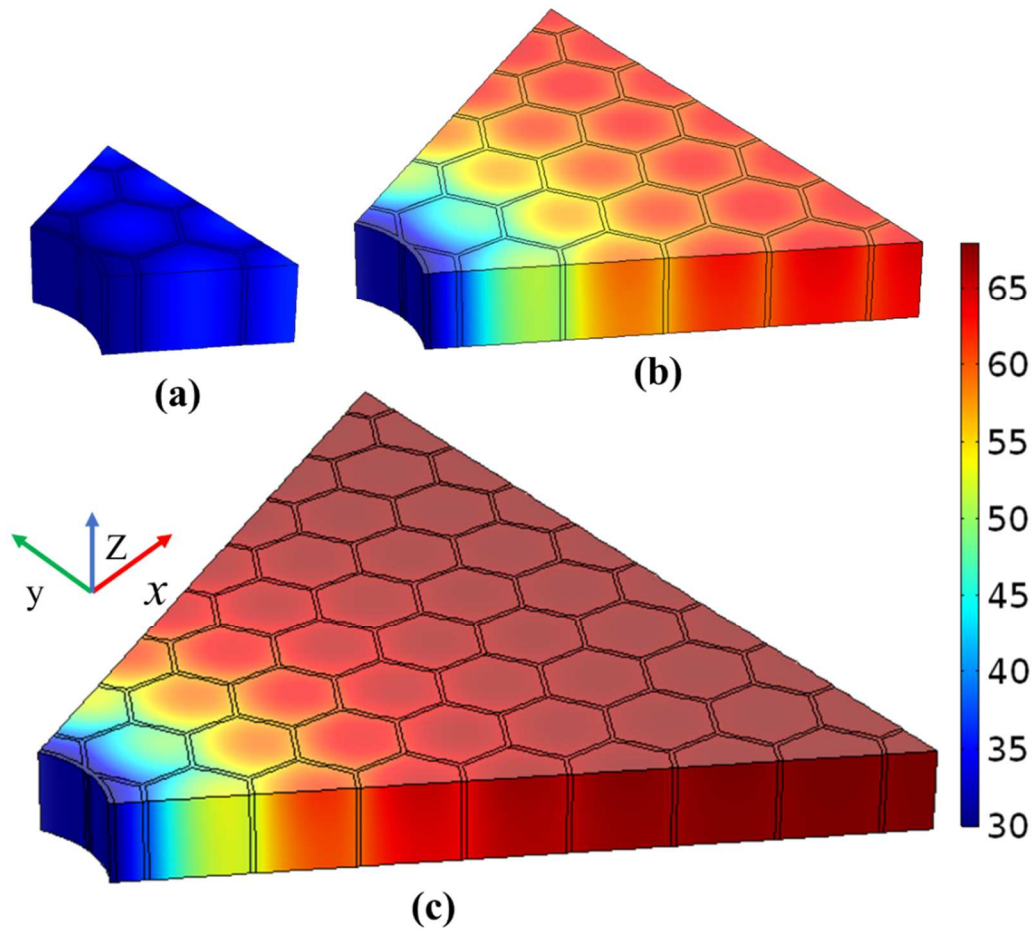
Fig. 11 Variation of (a) Temperature, (b) reaction advancement and (c) power output with time for different cell sizes; temperature and reaction advancement are presented for probe point P8

522 Further, the temperature variation, reaction advancement at probe point P8 and power output
 523 from the computational domain are presented in Fig 11 (a), Fig. 11(b) and Fig. 11 (c)
 524 respectively. The temperature for the minimum fin thickness is the highest and, vice versa,
 525 the temperature for the maximum fin thickness is the lowest which is understandable because
 526 it influences the thermal transport from the bed to the HTF as discussed above. For $\delta_{fin} =$
 527 0.001 m , $\delta_{fin} = 0.0015\text{ m}$, and $\delta_{fin} = 0.002\text{ m}$ the temperature at 120 min reaches to 32
 528 °C, slightly above its initial value of 30 °C, however for $\delta_{fin} = 0.0005\text{ m}$ its value is still
 529 around 59 °C because the hydration reaction is still in full swing as can be concluded from the
 530 reaction advancement. The reaction advancement at probe point P8 is presented in Fig. 11
 531 (b). From Fig. 11(b) it is observed that the reaction advancement reached around 0.98 at 120
 532 min, for the fin thickness greater than 0.0005 m, however, it reaches 0.68 for fin thickness
 533 0.0005 m. The power output from the TCM bed is presented in Fig. 11(c). Initially, the power
 534 output sharply increases and starts decreasing gradually after reaching its peak value. The
 535 maximum peak power is obtained for fin thickness $\delta_{fin} = 0.0015\text{ m}$, the minimum peak
 536 power for fin thickness of $\delta_{fin} = 0.0005\text{ m}$. In Fig. 11 (c) it is also observed that the power
 537 output with $\delta_{fin} = 0.002\text{ m}$ fin thickness is lower as compared to $\delta_{fin} = 0.0015\text{ m}$ because
 538 a larger fin thickness results in a larger volume of fin material and reduces the actual volume
 539 of the TCM which causes lower power output. Finally, it is interesting to note that for a lower
 540 fin thickness the peak power goes down but the power is more constant over time than for a
 541 higher fin thickness.

542 4.2.4. Effect of distance between two HTF heat pipe

543 Numerical simulations have also been conducted to see the effect of the distance between two
 544 HTF tube ($t_{gap,HTF}$). The simulations have been performed for $t_{gap,HTF}/2 = 0.045\text{ m}$,
 545 $t_{gap,HTF}/2 = 0.090\text{ m}$, and $t_{gap,HTF}/2 = 0.135\text{ m}$. The volumes of the porous K_2CO_3
 546 samples for $t_{gap,HTF}/2 = 0.045\text{ m}$, $t_{gap,HTF}/2 = 0.090\text{ m}$, and $t_{gap,HTF}/2 = 0.135\text{ m}$ are
 547 12.78 cm^3 , 59.49 cm^3 and 137.34 cm^3 respectively and the ratio of the porous K_2CO_3 samples
 548 to the metallic fins volume is fixed at 7.92. The obtained temperature contours at 15 min are
 549 presented in Fig. 12(a), Fig. 12(b) and Fig. 12(c) respectively. The temperature gradient near
 550 the HTF tube in the computational domain is smaller for a smaller distance between two HTF
 551 tubes. The temperature gradient in each cell near the HTF tube is also higher for the
 552 higher $t_{gap,HTF}/2$. For maximum $t_{gap,HTF}/2$, when moving away from the HTF tube the

553 temperature gradient in each cell starts decreasing. At the maximum distance from the HTF
554 tube, the temperature gradient is negligible. Further, temperature variation and reaction
555 advancement at probe point 8 and power output from the TCM bed is presented in Fig 13(a),
556 Fig. 13(b) and Fig. 13(c) respectively. It is evident that for higher values of $t_{gap,HTF}/2$ the
557 temperature at probe point 8 is the highest. For $t_{gap,HTF}/2 = 0.045$ m and 0.09m, the
558 temperature increases to its maximum value and then it starts decreasing. For minimum
559 $t_{gap,HTF}/2$ (0.045 m), the maximum temperature reaches 37.5 °C at around 5 min and starts
560 decreasing gradually with time and reaches 31 °C at 120 min. For maximum $t_{gap,HTF}/2$
561 (0.135 m), the temperature reaches 68 °C at 10 min and its value remains around 68 °C over
562 the whole time span. From the reaction advancement as presented in Fig. 13(b), it is observed
563 that the reaction advancement is higher for the lowest $t_{gap,HTF}/2$ in the initial stage of
564 reaction and becomes maximum for $t_{gap,HTF}/2 = 0.09$ m after 60 min. Further, the power
565 output of the TCM bed is also presented in Fig. 13 (c) for different $t_{gap,HTF}/2$ values. For all
566 its values the power output increases in precisely the same way. However, the smaller the
567 $t_{gap,HTF}/2$ value, the earlier the maximum is reached. The maximum power output is
568 achieved with the highest $t_{gap,HTF}/2$ because of the higher volume of the TCM bed.
569



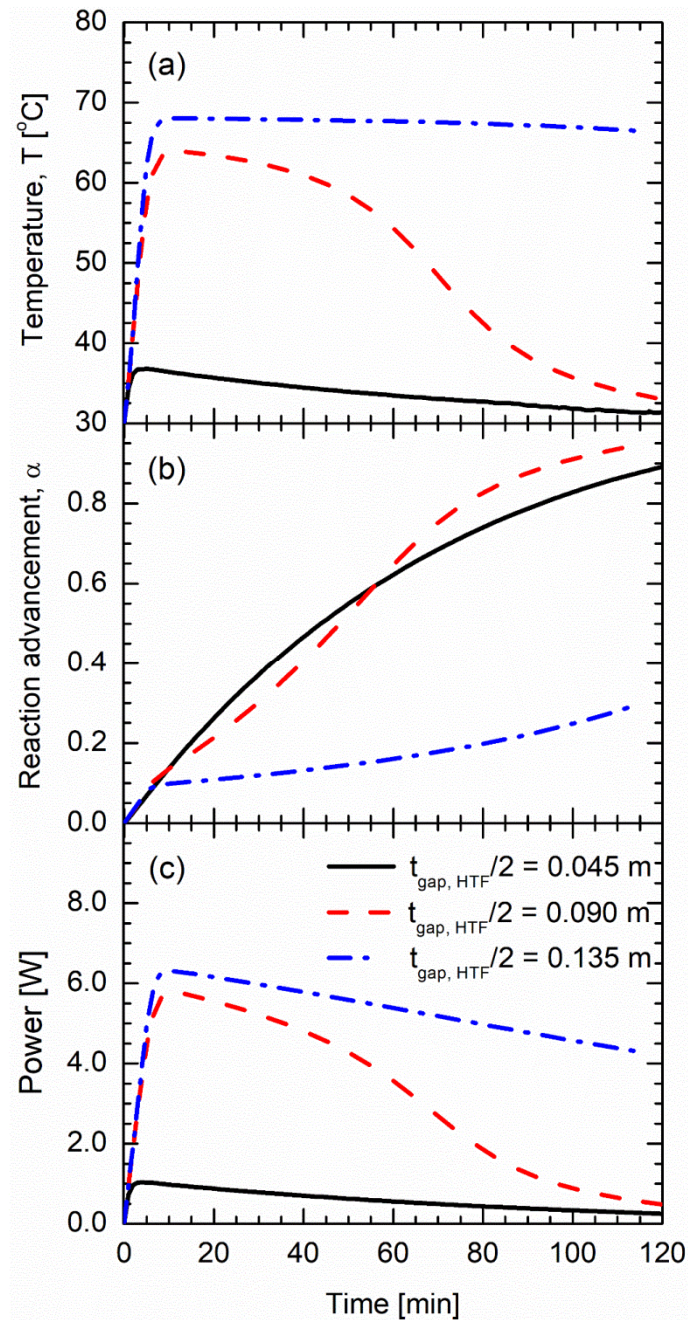
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Fig. 12 Temperature contours for different distance values between two HTF tubes

(a) $\frac{t_{gap,HTF}}{2} = 0.045 \text{ m}$, (b) $\frac{t_{gap,HTF}}{2} = 0.090 \text{ m}$, (c) $\frac{t_{gap,HTF}}{2} = 0.135 \text{ m}$ at $t=15 \text{ min}$



573

574 Fig. 13 Variation of (a) Temperature, (b) reaction advancement and (c) power output with
 575 time for different distances between two HTF tubes; temperature and reaction advancement
 576 are presented for probe point P8

577 **5. CONCLUSIONS**

578 A thermochemical energy storage system using potassium carbonate and water as the
 579 sorbent/sorbate reaction pair ($K_2CO_3/K_2CO_3 \cdot 1.5H_2O$) is studied numerically considering a
 580 three-dimensional fixed honeycomb heat exchanger bed filled with K_2CO_3 -particles. The

581 thermochemical bed is cooled from the center of the honeycomb heat exchanger by an HTF
582 flow. The developed numerical model for the reaction kinetics of potassium carbonate is
583 validated with experimental data in terms of reaction advancement. The results obtained
584 provide detailed insight into the temperature variation and reaction propagation in the
585 reactive solid TCM bed during discharging. A parametric study has been conducted to see the
586 effect on the heat transfer of the honeycomb cell size, the bed height, the honeycomb fin
587 thickness and the distance between two HTF tubes. It is concluded that an increase in bed
588 height, cell size and fin thickness affect the discharge process to a great extent. Increasing the
589 height of the bed will restrict the vapor flow within the bed whereas increasing the cell size
590 and decreasing the fin thickness of the honeycomb heat exchanger will reduce the heat
591 transfer to/from the bed due to poor conductivity properties. Increasing the distance between
592 two HTF tubes will result in an increase of the temperature maximum and, therefore, will
593 require heat transfer enhancement techniques if this temperature must remain below a certain
594 value (to avoid dehydration during hydration for example).

595 It can be concluded that the developed numerical model is a very powerful tool in predicting
596 all details of the physical phenomena taking place in the three-dimensional fixed honeycomb
597 heat exchanger bed packed with K_2CO_3 -particles. The model is also well suited for other
598 applications utilizing different TCMs and different heat exchanger configurations. Changes in
599 temperature, reaction advancement and power output with respect to geometry can easily be
600 investigated using a similar approach. The next step is the design and the test of a prototype
601 of the most optimal storage system equipped with honeycomb heat exchangers at a
602 significant scale. The test of this prototype will allow us to demonstrate the feasibility of the
603 potassium carbonate seasonal thermochemical storage process with a fixed bed honeycomb
604 heat exchanger configuration functioning with water vapor for the built environment.

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