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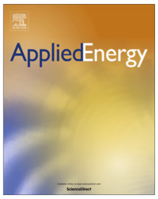

Modelling and experimental validation of a fluidized bed based CO_2 hydrate cold storage system

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HIGHLIGHTS

- CO_2 hydrate slurry has a high latent heat at temperatures in the range of 7–8 °C.
- Fluidized bed heat exchanger (FBHE) allows for continuous generation of hydrates.
- Hydrate production rate in the FBHE can be predicted using a crystal growth model.
- FBHE operation is possible up to 35 wt% in open systems and 45 wt% in closed systems.
- Energy savings up to 45% are possible using day/night gradient and hydrate storage.

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ABSTRACT

Latent heat thermal storage (LHTS) systems can be applied to minimize the discrepancy between energy supply and demand in cold applications. Combining this system with night time generation of CO_2 hydrate slurry can significantly reduce the investment costs for cooling purposes. These systems require hydrate generation temperatures around 8 °C and can, from an energetic point of view, contribute to significant energy savings. In this paper a numerical and experimental investigation is carried out for a shell-and-tube fluidized bed heat exchanger, combined with a hydrate slurry storage vessel. When required, heat can be removed from the storage by circulating the slurry through a heat exchanger which is part of the cold distribution system. The model of the fluidized bed heat exchanger is coupled with the model of the cold storage system. The phase change process is modelled by using a crystal growth model. The presented work provides experimental data for the thermal performance and hydrate generation of a fluidized bed based LHTS system for a CO_2 hydrate cold storage system.

1. Introduction

Space cooling is responsible for the largest part of the electricity consumption in office buildings. On account of global warming, longer working times and the desire for more comfort, the demand for cooling is increasing. This leads to a higher electricity consumption which is accompanied by further depletion of fossil fuel resources and aggravation of the global warming problem. Hence, there is necessity for more sustainable cooling technologies. Cold storage, as a method to increase the efficiency of conventional cooling systems, has received a considerable amount of attention [1–12]. Thermal Energy Storage (TES) systems are indispensable to minimize the discrepancy between energy supply and demand. Furthermore, the investment costs need to be reduced to make such applications more economically attractive. Producing cold during the night with low environmental temperatures can significantly contribute to economic advantages, specifically if the day/night temperature gradients are large.

Compared with sensible heat storage materials, for example water, CO_2 hydrate slurry has a higher energy storage density. According to de Sera et al. [13] the storage volume for a capacity of 10^6 J are 16 m^3 for water and 0.6 m^3 for CO_2 hydrate slurry with 30% solid concentration. Therefore, it is possible to store the same amount of energy with a much smaller volume which could result in lower investment costs. The cost reduction will be limited by the requirement of operating the storage vessel at higher pressure level. Moreover, isothermal heat storage and heat recovery minimize the energy losses [14]. A respectful number of cold storage applications are reported in literature with the application temperature below 10 °C and above 0 °C [9].

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Nomenclature

a	lattice constant (m)
A	area (m^2)
Ar	Archimedes number (–)
c_r	circulation ratio (–)
d	diameter (m)
D	diffusion coefficient ($m^2\,s^{-1}$)
g	gravity constant ($m\,s^{-2}$)
G	hydrate growth rate ($m\,s^{-1}$)
Δh_{hyd}	melting latent heat of hydrates ($J\,kg^{-1}$)
h	enthalpy ($J\,kg^{-1}$)
k	mass transfer coefficient ($m\,s^{-1}$)
M	molar mass ($kg\,kmol^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	hydration number (–)
N_0	Avogadro constant = $6.02214129 \times 10^{26}$ (molecules $kmol^{-1}$)
Nu	Nusselt number (–)
Nu_h	hydraulic Nusselt number $\alpha d_p \varepsilon/(\lambda_{slu}(1-\varepsilon))$ (–)
p	pressure (kPa)
Pr	Prandtl number (–)
$\dot{Q}$	heat flow (kW)
Re	Reynolds number (–)
Re_h	hydraulic Reynolds number $\rho_{slu} u_s d_p(\mu_{slu}(1-\varepsilon))$ (–)
Sc	Schmidt number (–)
Sh	Sherwood number (–)
T	temperature (K)
t	time (s)
u_s	superficial velocity ($m\,s^{-1}$)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
V	volume (m^3)
w	weight fraction ($kg\,kg^{-1}$)
x	molar fraction ($kmol\,kmol^{-1}$)
z	axial coordinate (m)

Greek

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
ε	bed porosity (–)
ϕ	volume fraction (–)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity (Pas)
ρ	density ($kg\,m^{-3}$)

Lower- and upper-script

$*$	equilibrium
eq	equilibrium
exp	experimental
fb	fluidized bed
hyd	hydrate
i	inner
in	at inlet
j	control volume level in the model
lam	laminar
m_hex	melting heat exchanger
o	outer
out	at outlet
p	particle of fluidized bed
pb	packed bed
ref	refrigerant
slu	slurry
sol	solution
sv	storage vessel
turb	turbulent
w	wall conditions

Abbreviations

COP	coefficient of performance
FBHE	fluidized bed heat exchanger
LHTS	latent heat thermal storage
PCM	phase change material
TES	thermal energy storage

Table 1
The candidate PCMs for cold storage in space cooling systems.

Solute	Melting point (°C)	Heat of fusion (kJ/kg)	Source
H_2O	0	333	Oró et al. [9]
Paraffin C_{14}	4.5	165	Abhat [20]
Microencapsulated tetradecane	5.2	215	Oró et al. [9]
CO_2	0–10	387.2	Lirio and Pessoa [21]
Paraffin C_{15}–C_{16}	8	153	Abhat [20]
Poly-glycol E400	8	99.6	Lane [22]
TBAB	10–12	263.0	Oyama et al. [23]

Criteria to select a suitable latent heat storage material for a particular application are [15,16]: a suitable phase change temperature in the desired operation range, a high latent heat value, a high thermal conductivity value, good cycling stability and small supercooling during solidification. Farid et al. [17] reviewed several TES with phase change materials (PCMs) and their applications. They highlighted the problems of supercooling, phase separation and thermal instability. The use of a fluidized bed heat exchanger reduces the required supercooling for phase change practically to 0 K. Meewisse [18] and Pronk [19] have developed a mathematical model of fluidized bed slurry generators. They derived the crystal growth rate and from it the solids concentration increase as the flow passes the heat exchanger. They further concluded that the temperature gradients are very low within the fluidized bed.

The main objective of this study is to predict and experimentally validate the transient performance of a fluidized bed LHTS system, combined with a CO_2 hydrate slurry storage system for cooling purposes. Continuous charging and discharging operation of the LHTS system can take place independently from each other. Further objectives are: the evaluation of CO_2 hydrate slurry as candidate PCM in the proposed application range (0 to 10 °C), the integration of the LHTS system with the fluctuation of the cooling demand, and investigation of the impact of operating conditions on system performance.