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Development of a numerical model for the reaction zone design of an aqueous sodium hydroxide seasonal thermal energy storage

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Abstract

This paper describes a thermochemical seasonal storage with emphasis on the development of a reaction zone for an absorption/desorption unit. The heat and mass exchange is modelled and the design of a suitable reaction zone is explained. A tube bundle concept is presented for the heat and mass exchangers and the most demanding working conditions they should fulfil are modelled and discussed. To estimate the performance of such a reaction zone and to design it, numerical models were developed and are described in this paper. Several parameters influencing these models were tested such as the sensitivity of the models to the correlation used to calculate the heat and mass exchanges, the tube diameter and the tube pitch influence. The final contribution of the tube bundle modelling is to size and design the heat and mass exchanger constituting the reaction zone. This work will be used as a basis for the reaction zone construction of an aqueous sodium hydroxide seasonal thermal energy storage prototype.

Keywords: Seasonal thermal energy storage; Solar thermal energy; Absorption; Desorption; Falling film; Tube bundle

1. Introduction

Solar thermal energy storage for heating and cooling systems is a priority goal in the renewable energy future. Seasonal storage using sensible thermal energy in materials (usually water) has two main disadvantages: comparably high thermal losses and a low volumetric energy density. Therefore, the activity of numerous research groups with various approaches aim at reducing the required building volume assigned for seasonal thermal storage (Hadorn, 2005). Phase-change materials (PCM) and thermo-chemical materials (TCM) are promising approaches with the potential for increased volumetric energy density. In a TCM based thermal storage system, thermal energy is used to separate the storage medium working pair in its components and reversing the process releases thermal energy through an exothermal reaction. A recent overview of sensible, latent and thermo-chemical storage concepts indicating the specific advantages and disadvantages can be found in Cabeza (2014).

As water vapour absorption in aqueous sodium hydroxide has a considerably higher volumetric energy density compared to sensible thermal storage systems, Weber and Dorer (2008) investigated a closed sorption heat storage

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Nomenclature

Ar	Archimedes number (–)
Cp	specific isobaric heat capacity (J/(kg K))
D	tube diameter (m)
f	Darcy friction factor (–)
Ga	Galileo number (–)
h	heat transfer coefficient ($W/(m^2\ K)$)
H	enthalpy (J/kg)
K	singular pressure loss coefficient (–)
L	tube length (m)
m	mass flow rate (kg/s)
N	number of tube rows (–)
n	current tube row item (–)
P	pressure (Pa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
R_f	Fouling factor ($m^2\ K/W$)
Re	Reynolds number (–)
T	temperature (K)
wt	NaOH mass fraction (kg_{NaOH}/kg_{sol})

Greek symbols

λ	thermal conductivity (W/(m K))
μ	viscosity (Pa s)
ρ	density (kg/m^3)
Γ	linear mass flux (kg/(m s))
φ	exchanged heat power (W)

Pre and suffixes

a	absorber
av	averaged
c	condenser
d	desorber
e	outside (of the tube)
ev	evaporator
i	inside (of the tube)
h	hydraulic
l	liquid phase
lv	liquid–vapor
r	regular
s	singular
sat	saturation conditions
t	for one column of tubes
th	thermal
tot	total incoming
trans	transition
v	vapour phase
w	wall
Δ	difference
Γ	per length unit

based on sodium hydroxide and water. In the present work, the reaction zone of an absorption/desorption concept with sodium hydroxide (NaOH) and water will be highlighted and investigated, focussing on the design and component improvement. The storage system functions as a thermally driven heat pump with seasonal separated batch process step operation. The charging process involving desorption and condensation is being performed during the warm seasons and the discharging process involving evaporation and absorption takes place during the cold seasons. Separate vessels contain the diluted and concentrated aqueous sodium hydroxide as well as the water – all tanks forming the storage capacity (kWh) of the system. The liquids are pumped to the relevant zones – forming the power (kW) zone of the system – for thermal charging as well as for discharging.

Heat and mass exchangers building the reaction zone are core components in this liquid sorption energy storage concept. The heat provided by solar collectors during the charging process in summer is used to vaporise a portion of the water contained in the diluted caustic soda solution (desorber) under reduced pressure. The caustic soda lye will then have a higher NaOH concentration. At the same time, the latent condensation heat (condenser) is released to the ground by means of a borehole – at this reaction zone development level no heat recovery is scheduled – and the liquid water as well as the concentrated solution are stored in separate tanks at room temperature. During discharging, the process is reversed: the ground heat is used to evaporate the water under reduced pressure (evaporator) and the absorption of the water vapour into the concentrated caustic soda solution releases heat (absorber). The caustic soda solution temperature will be increased to a level sufficiently high to satisfy the building's heating requirements in winter time (Weber and Dorer, 2008; Gantenbein et al., 2012). Because the process steps of charging and discharging are separated seasonally, it is one of the intentions of the current study to reduce the required storage volume by employing only one heat and mass exchanger for both absorption and desorption and another one for both condensation and evaporation.

In a first part the working principle of the seasonal storage as well as the heat and mass exchangers are described and the boundary conditions are clarified.

In a second part, the mathematical models used for the design of the reaction zone exchanger are explained. It was necessary to develop our own models as the type of heat and mass exchangers are not often used in the industrial domain within the boundary conditions required by the reaction zone of this storage (working with caustic soda and low mass flow rates).

These models were then used in a third part to design the tube bundles constituting the reaction zone and, among other to complete these design without fluid recirculation