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Design and optimization of solid thermal energy storage modules for solar thermal power plant applications

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HIGHLIGHTS

- An initial model is developed for a solid cylindrical heat storage unit.
- The analytical solution of the model is determined by using Laplace transform method.
- A new optimization method for the solid storage module design is proposed.
- The influence of design parameters on the storage cost is investigated.
- The optimization designs for various kinds of system requirement are studied.

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ABSTRACT

Solid sensible heat storage is an attractive option for high-temperature storage applications in terms of investment and maintenance costs. Typical solid thermal energy storage systems use a heat transfer fluid to exchange heat as the fluid flows through a tubular heat exchanger embedded in the solid storage material. The modified lumped capacitance method is used with an effective heat transfer coefficient in a simplified analysis of the heat transfer in solid thermal energy storage systems for a solid cylindrical heat storage unit. The analytical solution was found using the Laplace transform method. The solution was then used to develop an optimization method for designing solid storage modules which uses the system requirements (released energy and fluid outlet temperature) as the constraint conditions and the storage module cost as the objective function for the optimization. Optimized results are then given for many kinds of system configurations.

1. Introduction

Power generation using concentrated solar thermal energy is one of several promising renewable energy technologies with a great amount of worldwide research devoted to the development of concentrated solar energy systems in the last ten years [1,2]. Thermal energy storage (TES) is essential for concentrating solar power (CSP) plant applications. The main advantages of integrating a CSP system with thermal storage include extended utilization of the power block and life expectancy of components due to the reduction of thermal transients [3–5]. Therefore, TES systems give CSP plants an edge over photovoltaics or wind power [6].

There are three kinds of TES including sensible heat storage (SHS), latent heat storage (LHS) and thermo-chemical heat storage (TCHS) that uses reversible endothermic chemical reactions. LHS is based on the change of state of a material. The thermal energy is stored when the material changes state as the heat of fusion or heat of vaporization. Presently, the development of phase change material and design of the LHS systems have been widely investigated [7–11]. SHS uses solid or liquid media and involves storing energy in a material without phase change in the temperature range of the storage process. This technology is the most mature and has been widely used in CSP systems. Currently, the two-tank molten salt storage system with a high-temperature tank and a low-temperature tank for storing the molten salt is the most mature utility-scale TES system for CSP plants. Such systems have been applied in parabolic trough power plants including Andasol (1–3) in Spain, Archimede in Italy [12,13] and the power tower plant Gemasolar in Spain [14]. However, the disadvantages of this design are the very high cost of the material used as heat transfer fluid (HTF) and storage material, the high cost of the heat

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Nomenclature

a	inner radius of the cylindrical heat storage unit (m)
b	outer radius of the cylindrical heat storage unit (m)
C	specific heat (J/(kg K))
d_h	tube wall thickness (m)
d_i	inner diameter of the heat storage unit (m)
d_m	inner diameter of the main pipe (m)
d_o	outer diameter of the heat storage unit (m)
f	Darcy friction factor
h_E	corrected heat transfer coefficient (W/(m^2 K))
h	heat transfer coefficient (W/(m^2 K))
k_s	solid material thermal conductivity (W/m K)
L	heat storage unit length (m)
$\dot{m}$	mass flow rate (kg/s)
m_s	storage unit solid mass (kg)
N	number of heat transfer tubes
P	heat transfer surface perimeter of the cylindrical surface (m)
P_{pump}	pump power (kW)
p_l	total head loss (Pa)
$p_{l,main}$	head loss in the main pipe (Pa)
$p_{l,branch}$	head loss in the heat transfer tube (Pa)
p_m	local resistance loss (Pa)
Δp	pressure drop (Pa)
Q_{dis}	energy obtained by the fluid (kW h)
Q_L	heat loss from storage module (kW h)
$Q_{\max}$	maximum released energy from the storage module (kW h)
Q_s	released energy from storage unit (kW h)
Q_{total}	effective energy released from the storage module during the entire storage module life
q''_L	heat loss flux (kW/m^2)
R_c	total concrete material cost ($)
R_e	total cost of electricity for the pump ($)
R_i	total insulation material cost ($)
$R_{material}$	total material cost ($)
R_p	total pump cost ($)
R_s	total cost of heat transfer tube material ($)
R_{total}	total storage module cost ($)
r_c	heat transfer tube material cost per unit mass ($/kg)
r_e	electricity cost per kW h ($/kW h)
r_i	insulation material cost per unit area ($/m^2)
$r_{material}$	material cost per unit storage capacity ($/kW h)
r_p	cost of one pump ($)
r_s	heat transfer tube material cost per unit mass ($/kg)
r_{total}	unit storage cost ($/kW h)
s	Laplace transform parameter
S_f	wetted area in the tube (m^2)
S_i	insulation area (m^2)
S_s	solid material section area (m^2)
T	temperature (°C)
T_{amb}	ambient temperature (°C)
$T_{f,allow}$	allowed lowest fluid temperature (°C)
T_{fin}	inlet fluid temperature (°C)
T_{fout}	outlet fluid temperature (°C)
T_H	initial storage unit temperature (°C)
T_L	fluid inlet temperature (°C)
$\overline{T}_f$	mean fluid temperature (°C)
$\overline{T}_s$	mean solid temperature (°C)
$\overline{T}_{s,end}$	mean solid temperature at the end of the discharge period (°C)
ΔT	difference between T_H and T_L (°C)
t	time (s)
t^*	dimensionless time
t_{dis}	discharge time (h)
$t_{s,life}$	storage module life (year)
$t_{p,life}$	pump life (year)
U	average fluid velocity in the heat transfer tube (m/s)
U_m	average velocity in the main pipe (m/s)
$\dot{V}_f$	fluid volume flow (m^3/h)

Greek symbols

Λ	Laplace transform of temperature
σ	allowed lowest dimensionless fluid temperature
θ	dimensionless temperature
ρ	density (kg/m^3)
ζ	local fiction factor
η	diameter ratio

Subscripts

f	heat transfer fluid
s	solid storage material

Acronym

CSP	concentrating solar power
FEM	finite element method
HTF	heat transfer fluid
GA	genetic algorithm
LHS	latent heat storage
SHS	sensible heat storage
SQP	sequential quadratic programming
TCHS	thermo-chemical heat storage
TES	thermal energy storage

exchangers, and the risk of solidification of the storage fluid because of its relatively high melting point which increases the maintenance and operating costs [15]. Solid sensible heat storage using concrete or ceramic as the storage material is expected to be an attractive option due to its lower investment and maintenance costs [16–18].

Concrete energy storage provides a regenerative storage system where the storage module is cyclically heated and cooled by the HTF. The fluid typically flow through a tubular heat exchanger with a defined tube pitch that is imbedded in the concrete [19]. The feasibility of such systems has already been proven in laboratory scale tests [20].

A large number of material tests such as thermal cycling and strength tests have been carried out by Laing et al. [6,19] and John et al. [21] to develop and optimize the mixture of the high-temperature concrete material. Laing et al. [6] place graphite between the layers of precast concrete slabs to improve the heat transfer between the concrete and the heat changer tube. Finite element method (FEM) calculation results showed that this structure could reduce the number of tubes by 47%. Selvam et al. [22] investigated heat transfer within a passive system considering four kinds of fin configurations including rods, disks, plates, and spiral fins. Various fin thicknesses and spacing were considered for each fin configuration using 3D FEM models. Zhu et al. [23] added six graphite sheets around a smooth tube to enhance the heat transfer into the concrete storage unit. The results showed that the graphite sheets significantly increased the equivalent thermal conductivity of the concrete by 4.7 times.

The German Aerospace Center (DLR) successfully tested a concrete storage unit and a castable ceramic storage unit on the