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Heat transfer behavior of elemental sulfur for low temperature thermal energy storage applications

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ABSTRACT

Elemental sulfur provides a low-cost, high-performance thermal storage option for a wide range of applications and over an exceptionally wide range of temperatures (50 °C to over 600 °C). In previous efforts we have shown impressive performance for 200–600 °C, while in this study we examine the low-temperature (50–200 °C) thermal charge and discharge behavior of isochoric sulfur-based storage using a detailed computational model solving for the conjugate heat transfer and solid-liquid phase change dynamics. The model provides excellent agreement with experimental results. We show that sulfur exhibits lower viscosity because of reduction in the chain-length of polymeric sulfur caused by trace amounts of organic substances resulting in attractive charge and discharge performance. The results from the parametric analysis of pipe diameter on the charge and discharge heat transfer characteristics are used to develop a simple, generalized correlation that relates the transient sulfur temperature and liquid fraction evolution as a function of dynamically evolving buoyancy-Fourier number due to the solid-liquid phase change. This solid-liquid buoyancy-Fourier, $BF_{s\text{-}l}$, correlation can be used for effectively designing sulfur-based thermal energy storage systems for transient operation in low temperature applications.

1. Introduction

Thermal energy storage (TES) can significantly increase the capacity factor and provide operational flexibility for various industrial, residential and commercial applications. Some potential applications for TES include waste heat recovery in industrial batch processes to improve energy efficiency [1,2], dispatchable power generation from intermittent renewable sources such as solar [3–5], improving the overall CHP system economics by providing demand side management [6–8]. Overall, several studies have shown that TES is a valuable commodity for green growth and sustainable development [9–12].

The most researched TES topic for low temperature applications are latent based thermal storage systems which stores energy primarily in the form of solid-liquid phase transition of the phase change material (PCM) [13–17]. A comprehensive review by Kenisarin and Mahkamov [13] showed the utility of PCM storage in solar greenhouses, solar cooking systems, and building applications. Extensive characterization and review of the thermophysical properties of various inorganic and organic PCMs are presented in the literature [14,16]. Cunha and Earnes [17] presented a comprehensive review of PCM with phase transition temperatures between 0 and 250 °C. They identified eutectic mixtures with urea and inorganic salts as promising PCM candidates for temperatures in the range of 100–200 °C. A review of shell and tube, encapsulated packed bed, and encapsulated staggered cylinder latent heat storage configurations for integration with various process heating and cooling applications was also discussed. Longeon et al. [15] experimentally and numerically studied the heat transfer behavior of paraffin wax stored in vertical annulus during thermal charge and discharge. They showed the influence of natural convection heat transfer mechanism during melting and the conduction dominated heat transfer mechanism during solidification. In general, most PCM thermal energy storage options suffer from the challenges of low thermal and chemical stability [16–18], and high cost [13,16,19,20]. In fact, Kenisarin and Mahkamov [13] concluded that the cost of commercial PCM products such as paraffin waxes, salt hydrates are prohibitively expensive (3.8–8.2 $/kg), and active research on low cost materials (<1 $/kg) is required for large-scale applications.

Recently, Wirz et al. [21] proposed the use of elemental sulfur as the storage media for thermal energy storage applications. Elemental sulfur is cheap [22,23] and experiences negligible thermal and chemical degradation [24–26]. Although sulfur has modest

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Nomenclature

BF	Buoyancy-Fourier number
c	specific heat [J/kg K]
D	nominal pipe size [inches]
D_i	pipe inner diameter [m]
D_o	pipe outer diameter [m]
Fo	Fourier number
g	gravitational acceleration [m/s^2]
Gr	Grashof number ($Gr = Ra/Pr$)
h	heat transfer coefficient [W/m^2 K]
$h_{s\text{-}l}$	latent heat of fusion [kJ/kg]
h'	heat transfer rate per unit pipe length [W/m K]
k	thermal conductivity [W/m K]
Nu	Nusselt number
p	pressure [Pa]
Pr	Prandtl number ($Pr = \mu c/k$)
Q	energy stored/discharged per unit pipe length [kW h/m]
$\dot{Q}$	surface heat flux [W/m^2]
Ra	Rayleigh number
R_{th}	thermal resistance [K/W]
t	time [s]
T	temperature [°C]
V	velocity [m/s]

Subscripts and superscripts

avg	average
C	charge
D	discharge
i	inner/initial
L	latent
o	outer
s	sulfur
s-l	solid-liquid
T	total
w	wall

Greek symbols

β	thermal expansion coefficient [1/K]
θ	non-dimensional temperature
μ	viscosity [Pa s]
ρ	density [kg/m^3]
τ	strain tensor

Acronyms

CSP	concentrating solar power
HTF	heat transfer fluid
NPS	nominal pipe size
TES	thermal energy storage

latent heat of fusion (~52 kJ/kg [24]) compared to other PCMs, the negligible cost of sulfur (~0.06 $/kg [22,23]) makes it an attractive storage candidate even at low temperatures. The sulfur-based thermal energy storage (SulfurTES) comprises of elemental sulfur encapsulated inside sealed pipes and heat transfer fluid (HTF) flowing in the shell (Fig. 1). In previous studies, we reported a laboratory scale demonstration of the SulfurTES battery [27] and characterized the heat transfer mechanism inside the storage pipes of SulfurTES battery for temperature ranges between 200 and 600 °C [28,29].

The objective of this study is to characterize the isochoric heat transfer characteristics of sulfur stored inside the pipes at temperature ranges of 50–200 °C. Within the temperature range of interest, sulfur exhibits two important characteristics, one being the

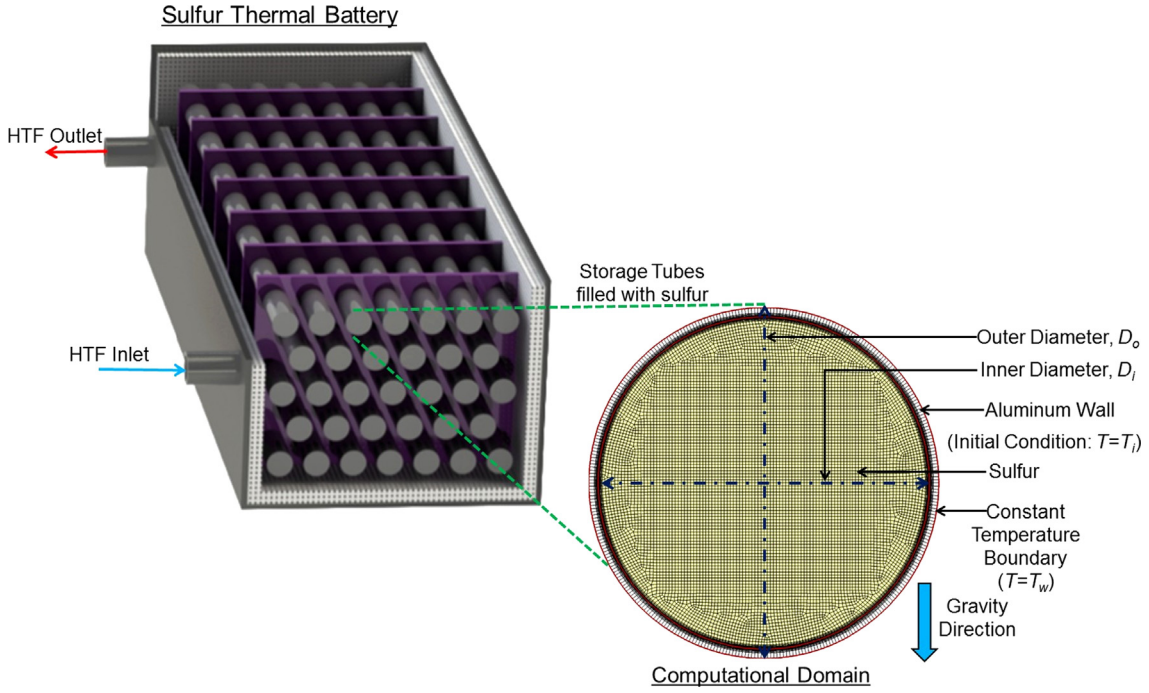

Fig. 1. Illustration of the sulfur thermal battery and schematic of the 2D computational domain with adopted mesh configuration, temperature boundary, and initial conditions.