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Circuitry arrangement optimization for multi-tube phase change material heat exchanger using genetic algorithm coupled with numerical simulation

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ABSTRACT

This study focused on circuitry arrangement optimization for a multi-tube phase change material heat exchanger. The optimization approach was developed based on a genetic algorithm approach coupled with numerical simulation and was aimed at maximizing the equivalent hot water output during the discharging process. Validated two-dimensional and three-dimensional simulations were used to support the genetic algorithm optimization process and to accurately investigate the thermal performance of the optimal circuitry arrangement. The results showed that adding more connections near the outlet side of the phase change material heat exchanger could lengthen the flow path in the high temperature zone, which was beneficial for a high mass flow rate condition of 1.68 kg min^{-1} with a 5% increment. Under medium and low mass flow rates of 1.2 kg min^{-1} and 0.5 kg min^{-1}, a 3% increment and a 6% decrement, respectively, were observed. It was found that different mass flow rates require their own optimal circuitry arrangements, and the arranged rules were not necessarily the same. Therefore, circuitry arrangement optimization should be performed according to the operating flow rate or designed range to maximize the optimization effect. The proposed optimization approach could serve as an effective way to improve the energy efficiency of multi-tube latent thermal energy storage systems.

1. Introduction

To adapt to the developments in energy efficiency and energy conservation, thermal energy storage is playing an increasingly important role in energy systems. Due to the high thermal storage density and the narrow range of phase change temperatures for phase change material (PCM), this material is widely used in thermal energy storage systems, is as well-known as latent thermal energy storage (LTES) and is getting more and more attentions in recent years [1].

In building energy conservation, PCM can be used for peak load shifting, solar energy storage and free cooling [2]. A PCM heat exchanger replacing the traditional water tank in air source heat pumps and solar domestic hot water systems can lower the energy consumption cost by storing the thermal energy during off-peak load periods or daytime [3]. Despite the high thermal storage density of such LTES occupying significantly smaller volumes compared to sensible heat storages, the low heat transfer coefficient between the PCM and the heat transfer fluid can be a great challenge to the thermal performance of a PCM heat exchanger in practical applications. To face this challenge, the geometry and configuration of the fins on the tubes embedded in the PCM have been widely studied and optimized [4]. Considering that a PCM heat exchanger generally consists of multiple tubes, the tube configuration and circuitry arrangement also require an in-depth optimization study to further improve the performance of PCM heat exchangers [5].

However, after reviewing the literature in Section 2, there are only a few research papers on the related optimization problem. In particular, it is lacking of efficient optimization approach for circuitry arrangement of multi-tube PCM heat exchangers. Therefore, this study focuses on the circuitry arrangement optimization for a multi-tube PCM heat exchanger as described in Section 3. In Section 4 the modeling and validation of the numerical simulations are conducted, followed by the genetic algorithm (GA) based optimization approach in Section 5. The final optimized circuitry arrangement, results and discussions are provided in Section 6, while the conclusions are summarized in Section 7.

2. A literature review of the related studies and optimizations

As a typical structure widely applied in LTES systems, the tube-based PCM heat exchanger has been studied in numerous simulations

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Nomenclature

Abbreviations

CFD	computational fluid dynamics
EA	evolutionary algorithm
EHWO	equivalent hot water output
GA	genetic algorithm
IGA	improved genetic algorithm
LTES	latent thermal energy storage
PCM	phase change material
PSO	particle swarm optimization
UDF	user defined function
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional

Symbols

A	area (m^2)
A_{mush}	mushy zone constant
c_p	specific heat (J kg K^{-1})
C	mark of tube connection sequence
d	hydraulic diameter (m)
F	fitness value (kg)
g	gravity acceleration (m s^{-2})
h	sensible enthalpy (J kg^{-1})
Δh	latent heat (J kg^{-1})
h_w	heat transfer coefficient (W m^{-2} K^{-1})
H	total enthalpy (J kg^{-1})
k	thermal conductivity (W m K^{-1})
l	length (m)
L	latent heat of the material (J kg^{-1})
n	individual number
Nu	Nusselt number
P	pressure (Pa)
P_i	probability to be selected
Pr	Prandtl number
q	water quantity (kg)
q_m	mass flow rate (kg min^{-1})
Q	heat quantity (J)
r	radius (m)
Re	Reynolds number
$\vec{S}$	source term (J kg^{-1})
t	time (s)
T	temperature (°C)
u	velocity (m s^{-1})
$\vec{u}$	velocity vector (m s^{-1})
V	volume (m^3)
Δ	difference

Greek symbols

β	liquid fraction
ε	a small value
ϕ	heat flux (W m^{-2})
μ	viscosity
ν	viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Superscripts

j	current time step
j-1	last time step

Subscripts

b	boundary
D	direct hot water output
e	equivalent hot water output
f	fluid
i	mark of individual
in	water inlet
$liquid$	melting temperature
m	mass flow rate
out	outlet
p	PCM
$path$	path wall
ref	reference
set	set value
$solid$	solidification temperature
$step$	time step
w	wall
1	current flow
2	previous flow

and experiments. Agyenim et al. [5] studied heat transfer characteristics experimentally in a multi-tube heat exchanger. The results showed an improvement in the heat transfer rate in the multi-tube system and revealed the requirement for further study of multi-tube arrangements. Tay et al. [6] conducted a numerical investigation and an experimental validation for tubes in a phase change LTES system with configured tubes in a unique arrangement. The authors provided details of the three-dimensional (3D) model, which could accurately predict the behavior of the LTES system during charging and discharging. Similarly, Allouche et al. [7] developed a 3D simulation model for an LTES system with a horizontal tube bundle. The simulation model was validated with experimental data for three different flow rates, and the results indicated that it could be used to optimize the tank design for improving the thermal performance. In addition, finned tubes and coil tubes were also studied by researchers to improve the heat transfer performance of LTES. Zauner et al. [8] demonstrated a 3D model for a fin-tube LTES system. Based on the model, the applicability of such a PCM storage design was investigated by adapting the mass flow control strategies and by altering the fin design parameters. Chen et al. [9] investigated numerically and experimentally an LTES system consisting of a spiral coil tube and a paraffin/expanded graphite composite PCM with enhanced thermal conductivity. The optimal design of the spiral coil tube was determined. The thermal conductivity enhanced by increasing the density of such a composite PCM could raise the LTES capacity and lead to a shorter charging time. In addition to the 3D simulation model, Tay et al. [10] developed a simplified 2D model to characterize a tube-in-tank PCM system with finned tubes and determined the number of fins to achieve the desired effectiveness. Ismail et al. [11] also studied the PCM solidification along a horizontal tube using a validated 2D model. The influence of the mass flow rate and the heat transfer fluid temperature were investigated.

Although these simulation methods were applicable to the investigation of thermal characteristics of PCM heat exchangers, the abovementioned studies only focused on specific PCM heat exchangers with certain or limited configurations. For configuration optimization studies, Esapour et al. [12] numerically studied the effect of changing the tubes' number from 1 to 4 in a multi-tube PCM heat exchanger. A 29% reduction in the melting time was obtained by increasing the number of tubes. A further study on this optimization problem was also conducted by Esapour et al. [13] to investigate the tubes' arrangement