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Comparative study of the transient natural convection in an underground water pit thermal storage

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HIGHLIGHTS

- The transient natural convection in a water pit thermal storage is investigated.
- The mechanism of temperature stratification caused by buoyancy is revealed.
- The most intense regions of convective heat transfer are pointed out.
- The position of the maximum velocity and its variation characteristics are presented.

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ABSTRACT

This study investigated the transient natural convection phenomenon in an underground water pit thermal storage with heat losses through the surrounding walls. An experimental test rig was built up, and a numerical model was developed to obtain the characteristics of the thermal stratification in the water pit thermal storage. Fluid properties are assumed to be constant, except for the density changes with temperature which is treated using the Boussinesq approximation. The simulations of temperature profiles are reasonably proved by experiments with the maximum relative errors of ± 9.77%. The results show that water temperature decreases close to the walls due to the heat losses, which leads to a downward flow along the inclined sidewalls. A slight upward flow occurs at the center of the water pit thermal storage, which lifts the warmer water to a higher level. As a result, the buoyancy-driven flow gradually builds up the thermal stratification in the water pit thermal storage. The modelling results also show that the values of the average Nusselt numbers on the inner surface of the inclined sidewalls and the bottom of the tank are much higher than that of the top thermal insulation layer. The thermal energy storage efficiency decreases rapidly in the first five minutes from 100% to 83.19% due to the intense heat transfer, and then tends to level off at the end of 40 min. The maximum velocity of the natural convection appears close to the upper part of the inclined sidewalls, and it decreases with the cooling process evolved. The present work has a valuable attempt to fill the gap in the existing studies and is useful for guiding the water pit thermal storage design.

1. Introduction

As the largest energy consuming sector in buildings, space heating and water heating are responsible for nearly 50%–60% of the total energy consumption and one-third of related greenhouse gas emissions [1–6]. Since the excessive use of fossil fuels leads to serious pollution and environmental consequences, people began to focus on the research of effective use of renewable energy [7–12]. However, renewable energy is always characterized by instability and discontinuousness due to their variation with the location, weather conditions, time and seasons of a year. Therefore, energy storage system is an essential technology for adjusting the intermittency and time discrepancy between energy

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Nomenclature

c_P	specific heat, $Jkg^{-1}K^{-1}$
E	internal thermal energy, kJ
e	internal thermal energy per unit mass, $kJ\,kg^{-1}$
$\vec{F}$	body force vector per unit volume
g	acceleration of gravity, ms^{-2}
Gr	Grashof number, $Gr = g\beta\Delta TL_{ref}^3/\nu^2$
H	height, m
HP	heat pump
h	convective heat transfer coefficient, $Wm^{-2}K^{-1}$
k	heat conductivity, $Wm^{-1}K^{-1}$
L	length, m
Nu	Nusselt number, $Nu = hL_{ref}/k$
p	pressure, Pa
Pr	Prandtl number, $Pr = \nu/\alpha$
Q	heat transfer rate, W
Ra	Rayleigh number, $Ra = g\beta\Delta TL_{ref}^3/\nu^2\alpha$
T	temperature, K
ΔT	temperature difference, K
t	time, s
$\vec{V}$	velocity vector
u	velocity in the x direction, ms^{-1}
υ	velocity in the y direction, ms^{-1}
w	velocity in the z direction, ms^{-1}
WPTS	water pit thermal storage

Greek symbols

α	thermal diffusivity of the fluid, $m^2\,s^{-1}$
β	fluid thermal expansion coefficient, K^{-1}
μ	dynamic viscosity of the fluid, $kg\,m^{-1}\,s^{-1}$
η	thermal energy storage efficiency, %
ρ	density, $kg\,m^{-3}$
δ	thickness, m
ϕ	particle size, m
Φ	general variable
ν	kinematic viscosity, $m^2\,s^{-1}$
λ	second viscosity coefficient
θ	slope angle, °

Subscripts

a	ambient air
ave	average
b	boundary
bottom	the value of a variable at the bottom
c	cover
cond	conduction heat transfer
conv	convection heat transfer
f	fluid
i	initial
in	inner wall
ins	insulation
o	outer wall
ref	reference
s	sand
ss	stainless steel
top	the value of a variable at the top
w	the value of a variable at the wall

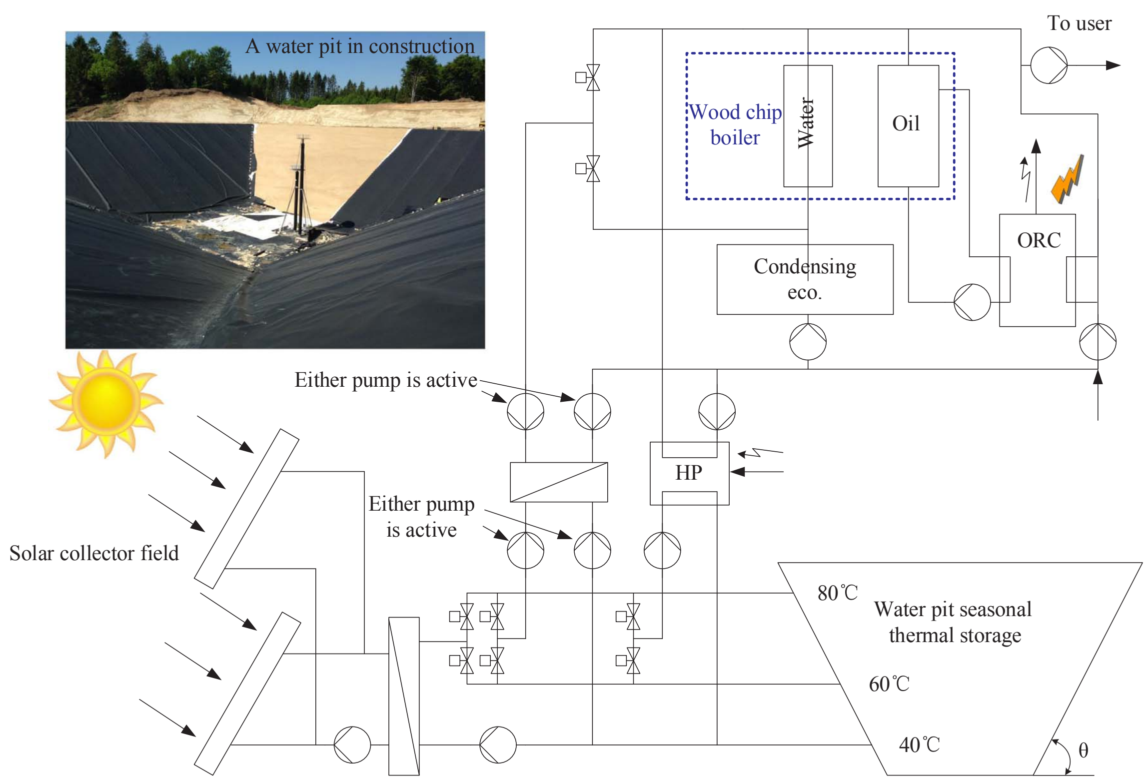

Fig. 1. Illustration of a solar heating system with water pit seasonal thermal storage in Denmark.