International Communications in Heat and Mass Transfer 76 (2016) 147–155

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Natural convection heat transfer of molten salts around a vertically aligned horizontal cylinder set☆

Yuanwei Lu *, Qiang Yu, Wenbin Du, Yuting Wu

Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education of China, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Available online 29 April 2016

Keywords:
Pair of cylinders
Molten salts
Natural convection
Nusselt number
Simulation

ABSTRACT

The heat transfer from the vertical arrays of a set of equally spaced cylinders in molten salts is studied numerically to obtain the laminar natural convection heat transfer mechanism of molten salts around a vertically aligned horizontal cylinder set. Simulations are performed for arrays of 2–10 horizontal cylinders at a Rayleigh number based on a cylinder diameter between 2×10^3 and 5×10^5. Results show that the natural convective heat transfer of molten salts from the bottom cylinder of the array remains the same as that from a single cylinder. By contrast, the downstream cylinders may either be enhanced or reduced mainly depending on their location in the array and on the tube spacing. Heat transfer dimensionless correlating equations are proposed for any individual cylinder in the two vertically aligned horizontal cylinders. The heat transfer mechanism from the horizontal cylinders set in a vertical array is also simulated, and the results show that cylinder spacing can influence the average heat transfer rate around the whole tube array. Thus, in real applications, adjusting the cylinder spacing better enhances the average heat transfer from the whole tube array.

1. Introduction

Increasing energy demands and environmental pollution have become key global problems, which drive the development of the utilization of renewable energy. Concentrated solar power (CSP) technology is a promising way to convert solar energy into electricity because it can be easily integrated with thermal energy storage (TES), through which excess solar energy can be collected and stored as thermal energy to fulfill 24 h power generation [1]. This energy can also be dispatched at will for conversion to electricity energy through a traditional Rankin steam power cycle at the hours of peak demand after sunset. As one of the most useful heat transfer and energy storage medium, molten salts are used in many commercial solar thermal power plants. The two-tank indirect energy storage system is currently widely used in the world. In this case, the collected solar energy is transferred first to molten salts and then to steam separately with oil-to-salt and salt-to-steam heat exchangers, respectively [2–3]. Therefore, most studies mainly focus on the forced convection heat transfer of molten salts [4–8].

However, the primary disadvantage of the two-tank indirect energy storage system is its high cost. For example, a thermal storage of 7.5 h in the very recent 50 MWe Andasol solar trough power plant in Grenada requires 28,000 tons of nitrate salts [3], which can cause a huge initial investment and high maintenance cost. Given this concern, a cost-reducing alternative thermocline single-tank TES technology is proposed and being studied. In a thermocline-type TES tank, hot and cold media are stored in the same tank, thereby eliminating one of the costly storage tanks required in a two-tank configuration. Given that nitrate salt is used as heat transfer fluid and storage medium, the energy storage temperature can be increased from the limit of 390 °C (for oil) to 565 °C (for molten salts), thereby reducing the required quantity of nitrate salt [1]. However, the primary problem for thermocline single-tank TES systems is the thermal ratcheting of the tank wall, which can cause the tank wall to expand during charging and to contract during discharging [1]. This cyclic charging and discharging process can lead to a catastrophic rupture of the tank. Therefore, an alternative single-tank TES technology must be sought.

The use of immersed helical coiled tube heat exchanger inside a single tank to meet the requirement of energy charging and discharging can potentially result in a remarkable reduction of cost. The storage side heat transfer of all the immersed heat exchangers occurs via natural convection. Vaivudh et al. [9] analyzed the heat transfer of a high TES with a heat exchanger immersed in an oil tank for a solar trough power plant and calculated the fluid temperature in a single-tank system with the principle of energy balance and heat convection. However, the natural convection heat transfer of oil around the helical coiled tubes was not provided. Probhanjan et al. [10] studied the natural convection heat transfer of water from the helica coiled tubes and determined that the correlation of Nusselt (Nu) number and Rayleigh (Ra) number can be well predicted using the coil height as the characteristic length. Gaggioli et al. [11–12] and Pizzolato et al. [13] proposed the

☆ Communicated by W.J. Minkowycz.
* Corresponding author.
E-mail address: luyuanwei@bjut.edu.cn (Y. Lu).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.04.022
0735-1933/

Nomenclature

D	diameter of cylinder [m]
L	length of cylinder [m]
X	a cylindrical center distance to the center of the bottom cylinder [m]
H	separation distance between bottom and top cylinders [m]
g	acceleration caused by gravity [m/s^2]
Ra	Rayleigh number
Pr	Prandtl number
Nu	Nusselt number
Ge	Gebhart number
T_s	surface temperature of cylinder [K]
T_0	ambient temperature of fluid [K]
T_m	average temperature [K]
S	pitch [m]
H	heat transfer coefficient [W/(m^2·K)]
u;v	velocity components [m/s]

Greek symbols

β	coefficient of thermal volume expansion [K^{-1}]
c_p	molten salt specific heat [J/(kg K)]
α	thermal diffusivity[m^2/s]
λ	thermal conductivity [W/(m K)]
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
μ	dynamic viscosity[N s /m^2]

Superscripts

L	lower cylinder
U	upper cylinder

Subscripts

s	surface of the cylinder
o	free stream condition
conv	convection

innovative concept of a TES system based on a single-tank configuration using stratifying molten salts as both heat storage medium and heat transfer fluid, as well as an integrated steam generator. These studies show that the single-tank TES system is the research direction for cost reduction and that the natural convection heat transfer of molten salts around coil tubes is very important for the design of a single-TES tank. However, only few studies on the natural convective heat transfer of molten salts around coil tubes have been reported at present. Thus, this study focuses on this matter to determine the natural convection heat transfer mechanism around an array of horizontal cylinders, which can be the basis for the design of a single-TES tank in solar thermal power generation.

Although few studies have been conducted exclusively on the natural convective heat transfer of molten salts [14], the natural convective heat transfer of other fluids, such as water and air, around an array of horizontal cylinders can be a research basis. In 2007, Yousefi and Ashjaee [15] investigated the laminar free convection heat transfer from a vertical array of horizontal isothermal elliptic cylinders in air. They determined that the natural heat transfer of air around an array cylinder is slightly different from that around a single cylinder at a different Ra number and cylinder spacing (S/D). Reymond et al. [16] studied the natural convection heat transfer from a pair of vertically aligned horizontal cylinders in water by experiment and determined that the heat transfer from the lower cylinder is unaffected by that from the upper cylinder. The Nu number of the lower cylinder is also the same as that of a single cylinder. However, the heat transfer from the upper cylinder is affected by the cylinder spacing. For $S/D = 2$, the maximum Nu number occurs at the bottom of the upper cylinder. The overall heat transfer from the upper cylinder can be enhanced by increasing the cylinder spacing (S/D) to 3.

Marsters [17] studied the natural convection heat transfer properties of a vertical array of heated cylinders. The results revealed that the heat transfer of the upper cylinder can be as much as 50% less at a small spacing or 30% more at a large spacing than that of the lower cylinder. Sparrow and Niethammer [18] studied the free convection heat transfer from an array of two vertically separated cylinders for S/D values varying from 2 to 9. The results indicated that the heat transfer of the upper cylinder increases with an increase in S/D. The heat transfer of the upper cylinder does not increase further when the S/D reaches 9, and the maximum Nu number is obtained when S/D varies from 7 to 9. Farouk and Guceri [19] conducted a numerical study on the natural convection heat transfer from two vertically aligned cylinders with different S/D values and Ra numbers. The Nu number of the upper cylinder increases when the Ra number increases within $10^3 < Ra < 10^4$ and $S/D > 2$. The Nu number of the upper cylinder always increases at any cylinder spacing when $Ra = 10^5$.

These works show that many studies on natural convection heat transfer around cylinder arrays in air or water have been conducted both experimentally and numerically [15–23]. However, few studies have given attention to the natural convection heat transfer of molten salts around the vertical arrays of a horizontal cylinder. This study focuses on the natural convection heat transfer of molten salts around the vertical arrays of a horizontal cylinder via the commercial software ANSYS CFX.

2. Physical model and numerical methods

2.1. Single-tank TES mechanism

Fig. 1 shows the schematic drawing of a single-tank TES system. Two immersed coiled tube heat exchangers and a cylindrical baffle are located in a vertical molten salt storage tank. A heat exchanger is located at the bottom and center of the storage tank, whereas the other is placed at the top of the annular gap formed by the open-ended baffle and tank wall. The high-temperature oil coming from the solar collector flows through the bottom heat exchanger of the storage tank to charge the

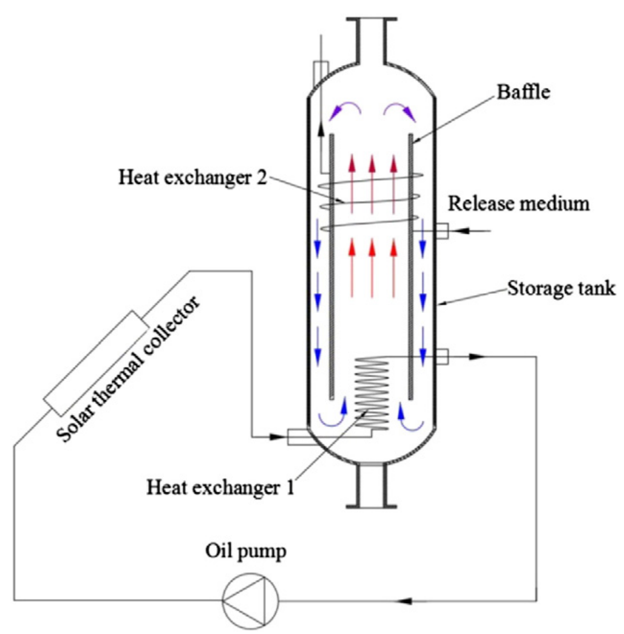

Fig. 1. Schematic of a single-tank TES system.