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Effect of baffle and shroud designs on discharge of a thermal storage tank using an immersed heat exchanger

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ABSTRACT

Heat exchangers immersed in thermal storage tanks are an increasingly popular way to charge and/or discharge energy from the tank. The present experimental study investigates the effects of different baffle and shroud configurations on heat transfer to an immersed copper coil heat exchanger during discharge of a thermal storage tank. The baffle-shrouds create annular regions with the tank wall within which the heat exchanger is located. Negatively buoyant plumes form from the heat exchanger and are directed by the shroud, which surrounds the heat exchanger, into the annular baffle below and through the baffle to the bottom of the tank, while water from the top of the tank is drawn into the top of the shroud to flow over the heat exchanger. Experiments are conducted in 300 L unpressurized storage tank filled with initially isothermal water at 60 °C. Water flows through the coiled copper tube heat exchanger placed at the top of the tank at a rate of 0.1 kg/s and with an inlet temperature of 20 °C. Transient heat transfer rate, produced water temperature, fractional energy discharge, temperature distributions in the tank, and Nu_D–Ra_D correlations are used to assess how the baffle-shrouds affect tank performance. The three baffle-shroud configurations represent different degrees of fidelity to numerical optimization studies in the literature. However, the simplest design and the one with the least fidelity to those studies—a straight baffle-shroud with a constant width of twice the heat exchanger diameter—performs best by all measures considered. The straight baffle-shroud increases the storage-side convective heat transfer by 27% in the first 90 min of discharge relative to a control experiment with no baffle-shroud. The improved heat transfer is attributed primarily to increased velocity over the heat exchanger, though the ∼2 °C thermal stratification generated by the baffle-shroud also contributes. The other baffle-shrouds have increasingly narrow baffle regions, which results in lower velocities but slightly higher thermal stratification. The benefit of the slight improvements in thermal stratification is outweighed by the cost of the decreased velocity over the heat exchanger.

1. Introduction

Solar thermal systems remain an elegant way to capture diffuse thermal energy from the sun and use it for similarly low energy density domestic hot water and space heating applications. Solar thermal systems minimize consumption of fossil fuels and emissions of greenhouse gases, a quality that is increasingly imperative as climate change predictions become more urgent (IPCC, 2014). Though low natural gas prices currently make the economics of solar thermal systems challenging in many markets, natural gas will not remain inexpensive indefinitely. Thus, decreasing the cost and/or improving the performance of solar thermal systems remains a worthwhile goal.

Heat exchangers immersed in water storage tanks can be used to charge or discharge thermal energy. Immersed heat exchangers provide several economic advantages over other charge/discharge options by allowing for unpressurized tanks and eliminating the need for pumps. The immersed heat exchanger is located strategically in the tank, generally to take advantage of the greatest temperature difference between the storage fluid and the heat exchanger working fluid. For example, for discharge, the heat exchanger is best placed at the top of the tank where the water is hottest. The cold plumes that form on the heat exchanger will descend into the tank and mix with the storage fluid.

For highly conductive heat exchanger materials like copper, the dominant thermal resistance for an immersed heat exchanger is that due to storage side natural convection, so it must be the focus of any efforts to improve overall heat transfer. There are two potential ways to improve natural convection in a thermal storage tank: (1) by increasing the velocity of the storage fluid as it flows over the heat exchanger and (2) by increasing the temperature difference between the storage fluid and the heat exchanger wall via enhanced thermal stratification. Several studies investigate the use of a baffle or baffle and shroud in both experimental and commercial tanks to passively control the flow

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Nomenclature

$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	heat transfer rate, W
A	outside surface area of the heat exchanger, m^2
C	coefficient for the Nusselt-Rayleigh correlation for natural convection
c_p	specific heat, J/kg °C
D	diameter of the heat exchanger, mm
f	fractional energy discharge of the storage tank
h	convective heat transfer coefficient, W/m^2 °C
H_{sh}	height of the shroud, mm
L_b	length of the baffle, mm
Nu_D	Nusselt number, $\frac{hD}{k}$
$Nu_{M/F/N,D}$	Nusselt number for the mixed (M), forced (F), and natural (N) convection components.
Pr	Prandtl number, $\frac{\nu}{\alpha}$
r	radial coordinate, $r = 0$ at the center of the tank, mm
Ra_D	Rayleigh number, $\frac{g\beta d^3(T_\infty - T_W)}{\nu\alpha}$
Re_D	Reynolds number, $\frac{uD}{\nu}$
t	time, min
T_f	film temperature of the water, $\frac{T_\infty - T_w}{2}$, °C
T_w	average heat exchanger wall temperature, °C
T_∞	temperature of the water approaching the heat exchanger, °C
T_{in}	heat exchanger inlet temperature, °C
T_{out}	heat exchanger outlet temperature, °C
$T_{S,0}$	initial volume-averaged storage fluid temperature, °C
T_S	volume-averaged storage fluid temperature, °C
u	velocity of storage fluid over the heat exchanger, m/s
W_b	width of the baffle, mm
W_{sh}	width of the shroud, mm
z	vertical coordinate, $z = 0$ at the bottom of the tank, mm
ΔT_o	storage side temperature difference, T_∞–T_w, °C
ΔT_{strat}	increase in T_∞ relative to a fully mixed tank, T_∞–T_S, °C

field in the tank with the goal of improving heat transfer via one or both of those means (Boetcher et al., 2010, 2012; Chauvet et al., 1993; Drück, 2002; Drück and Bachmann, 2002; Drück and Hahne, 1998; Haltiwanger and Davidson, 2008; Mote et al., 1992; Su and Davidson, 2008; Zemler and Boetcher, 2014). Here, we use "shroud" to describe barriers that surround a heat exchanger and isolate both it and the buoyant plumes that form from it from the rest of the tank, and "baffle" to describe barriers that direct the flow of those plumes in the tank. Many of the commercial and experimental apparati were designed to increase thermal stratification, but had limited success (Chauvet et al., 1993; Drück, 2002; Drück and Bachmann, 2002; Drück and Hahne, 1998; Mote et al., 1992).

Here, we investigate the effects of different baffle and shroud configurations on heat transfer to an immersed copper coil heat exchanger during discharge of a thermal storage tank. The cylindrical baffle-shroud configurations create annular regions with the tank wall, within which the heat exchanger is situated, as illustrated in Fig. 1. The negatively buoyant plumes from the heat exchanger are directed by the shroud to the annular baffle and through the baffle to the bottom of the tank, while water from the top of the tank is drawn into the top of the shroud to flow over the heat exchanger. The effect of a straight baffle-shroud, in which the width of both the shroud and baffle are identical and constant, on heat transfer to an immersed coil heat exchanger has been studied experimentally (Haltiwanger and Davidson, 2008) and numerically (Su and Davidson, 2008). In the experiments, the straight baffle-shroud maintained existing stratification in an initially stratified tank, but only created a 1 °C temperature difference between the bottom and top of the tank in an initially isothermal tank. The tanks in experiments without the baffle-shroud were fully mixed (i.e. remained isothermal). The small stratification generated by the baffle-shroud did not significantly affect heat transfer. However, the presence of the straight baffle-shroud increased convective heat transfer by 10–20%, based on Nusselt-Rayleigh correlations. Both studies attributed the observed increase in heat transfer to increased storage fluid velocity (Haltiwanger and Davidson, 2008; Su and Davidson, 2008).

A subsequent series of numerical investigations attempted to optimize baffle and shroud configurations using a 2D simulation of a single, infinitely long cold cylinder in a hot water store (Boetcher et al., 2010, 2012; Zemler and Boetcher, 2014). These studies optimized various geometric parameters relative to the cylinder diameter, D, including baffle length, L_b (Boetcher et al., 2010) and width, W_b (Zemler and Boetcher, 2014), and shroud height, H_{sh} (Boetcher et al., 2012). A general schematic of their simulated geometry is shown in Fig. 2. A model of a baffle placed below the cold cylinder with no shroud, demonstrated that the baffle length should be at least $25D$ to ensure fully developed flow for $Ra_D \leq 10^7$ (Boetcher et al., 2010). They investigated the effect of a shroud, parametrically varying its height while consistently defining the shape by a radius of curvature of D, and found that heat transfer was best with the highest shroud investigated, which extended above the top of the cylinder ($H_{sh} = 1.5D$) (Boetcher et al., 2012). They parametrically varied the width of the baffle, and found that the optimal baffle width was $0.75D$ (Zemler and Boetcher, 2014).

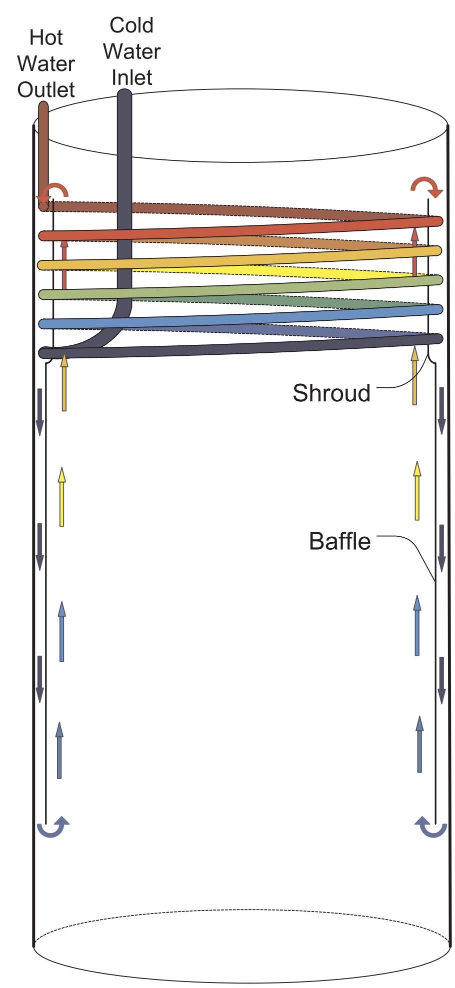

Fig. 1. Sketch of vertical cylindrical storage tank with an annular baffle and shroud and immersed coil heat exchanger. Arrows indicate flow direction.