Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 122 (2015) 472–485

SOLAR ENERGY

www.elsevier.com/locate/solener

Selection of permeability for optimum performance of a porous tube thermal stratification manifold

Shuping Wang, Jane H. Davidson *

Mechanical Engineering Department, University of Minnesota, 111 Church St SE, Minneapolis, MN 55414, USA

Received 20 July 2015; received in revised form 31 August 2015; accepted 15 September 2015
Available online 8 October 2015

Communicated by: Associate Editor Halime Paksoy

Abstract

In this study, we investigate the ability of porous tubes to maintain thermal stratification in a water storage tank in comparison to a top-mounted inlet pipe. Transient distributions of temperature and velocity are presented for operating conditions and a tank geometry representative of solar domestic hot water systems using a transient two-dimensional computational fluid dynamic model. The stratification in the tank is quantified by a dimensionless exergy efficiency. The results demonstrate the importance of selection of the permeability of the manifold on performance. A porous manifold improves thermal stratification for intermediate charging, regardless of the choice of permeability. Over a large range of Richardson number, the manifold is most effective for a dimensionless permeability, defined by the ratio of the pressure drop across the porous wall to the axial pressure gradient, equal to 0.02. Such a manifold will deliver the fluid to the tank in a narrow band at the vertical position of neutral buoyancy and will prevent suction of warmer fluid stored at the top of the tank into the manifold. For top charging the porous manifold is comparable in performance to a well-designed inlet pipe. Recommendations of selection of porous material based on dimensionless permeability are provided.

Keywords: Sensible storage; Exergy; Heating; Solar; Stratification; Manifold

1. Introduction

Thermal stratification of solar water storage tanks improves solar collector efficiency and the quality of hot water delivered to the load (e.g., Han et al., 2009; Hollands and Lightstone, 1989). Wuestling et al. (1985), Andersen and Furbo (2007) predict an ideally stratified tank would provide 15–37% higher solar fraction than that provided by a fully mixed tank. Establishing and maintaining a high degree of thermal stratification requires control of the fluid motion within the tank. The need for flow control is most critical during charging when the inlet fluid is cooler than the fluid stored at the top of the tank. With a conventional top-mounted inlet pipe the fluid entering the tank forms a descending thermal plume which entrains tank fluid and creates large scale mixing (Fig. 1a) (List, 1982; Turner, 1986). The entrainment flow rate has been estimated to be seven times the inlet flow rate (Phillips and Pate, 1977). The descending plume may carry sufficient momentum to destabilize the density interface between layers of different temperature.

Numerous efforts have been devoted to develop stratification manifolds to prevent destabilization and mixing. Concepts include flexible fabric manifolds (Andersen et al., 2008, 2007; Davidson and Adams, 1994; Gari and Loehrke, 1982), rigid pipes with non-return outlet valves

* Corresponding author. Tel.: +1 612 626 9850.
E-mail addresses: wang2807@umn.edu (S. Wang), jhd@umn.edu (J.H. Davidson).

http://dx.doi.org/10.1016/j.solener.2015.09.018
0038-092X/

Nomenclature

a	coefficient for thermocline thickness
A	cross-sectional area of the manifold
c_p	specific heat of water (kJ/kg/K)
D	inner diameter of the manifold, $D = 2R_i$
e_x	specific exergy (J/kg)
E_x^*	dimensionless exergy efficiency
g	Standard gravity (m^2/s)
k	thermal conductivity (W/m/K)
K	permeability of the porous manifold (m^2)
$\tilde{K}$	dimensionless permeability, $\tilde{K} = 2KL\dot{m}_{in}/\pi\mu\delta R_i^3$
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
Δp	differential pressure, $\Delta p = p - p_t$
r	radial coordinate (m)
R	radius (m)
Re_D	Reynolds number, $Re_D = \rho_{in}\bar{u}_{in}D/\mu_{in}$
Ri_L	Richardson number, $Ri_L = gL\beta_{in}(T_H - T_C)/\bar{u}_{in}^2$
s	entropy (J/K)
t	time (s)
T	temperature (°C)
$\mathbf{u}$	velocity vector
$\bar{u}_{in}$	average velocity at inlet, $\bar{u}_{in} = \dot{m}_{in}/\pi R_i^2\rho_{in}$
z	vertical coordinate (m)

Greek letters

ε	porosity
δ	thickness (m)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)

Subscripts

C	cool temperature
eff	effective
f	fluid
H	hot temperature
i	inner radius of the manifold
in	inlet to the manifold
L	depth of penetration of a free buoyant jet
mix	mixed state
mf	manifold
o	reference state or the outer radius of the manifold
out	outlet
p	porous region
r	radial direction
s	solid or suction
st	stratified state
t	tank
z	vertical direction

(Andersen et al., 2008; Shah et al., 2005), and rigid porous manifolds with (Gari and Loehrke, 1982; Loehrke et al., 1979, 1978; Sharp and Loehrke, 1979; Wang and Davidson, 2014) and without (Brown and Lai, 2006; Yee and Lai, 2001) vertical hydraulic resistance elements. A manifold should deliver the inlet fluid to the tank at the level of neutral buoyancy, prevent mixing of tank and inlet fluid within the manifold itself, and minimize conduction of heat across the manifold surface. Mixing in the manifold occurs if fluid from the tank is sucked into the openings in the manifold that are intended for outward flow into the tank (Fig. 1b). In addition, an effective manifold should maintain stratification even as the operating conditions change (i.e. inlet temperature, tank temperature distribution, and inlet mass flow rate). This adaptability to transient conditions is one of the most difficult design challenges.

In the present study, we consider the performance and design of porous tube without internal resistance elements because it is arguably the most conceptually simple design. Such a tube could be made of a number of porous materials, including rolled screen, fabric, open cell plastic foam, or sintered porous plastic. Fluid from the collector enters the porous tube and then flows into the tank through the porous wall. The lower end of the tube is closed to prevent fluid from passing directly through the tube. The important design challenge is to select the permeability of the porous material so the inlet fluid enters the tank in a narrow region at the vertical height where the fluid is neutrally buoyant with respect to the storage fluid and suction into the manifold is minimized.

Prior study of the porous tube manifold provides valuable insight to its behavior but is limited in scope to numerical analysis (Yee and Lai, 2001) of charging a cooler tank (referred to as top charging because the desire is to place the incoming warmer fluid at the top of the tank), and experimental observations (Brown and Lai, 2011) of a specific manifold during top and intermediate charging (where the incoming fluid is at a temperature cooler than that stored at the top of a thermally stratified tank but warmer than that stored at the bottom of the tank). One difference between the current and the prior work is the arrangement of the manifold in the tank. In the prior work, the outlet of the manifold was connected directly to an outlet port at the bottom of the tank, allowing the inlet fluid to pass through the tank. In the present work, the manifold is closed at the bottom. This arrangement represents the anticipated situation in a solar storage tank. Yee and Lai's (2001) numerical study suggests that the porous tube is not beneficial for top charging. For intermediate charging, a flow visualization study implies greater promise (Brown and Lai, 2011). However, it is likely that