Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 85 (2011) 1409–1417

SOLAR ENERGY

www.elsevier.com/locate/solener

Enhanced thermal stratification in a liquid storage tank with a porous manifold

N.M. Brown [a], F.C. Lai [b,*]

[a] School of Engineering, University of Technology, Kingston, Jamaica
[b] School of Aerospace and Mechanical Engineering, University of Oklahoma Norman, OK 73019, United States

Received 20 November 2008; received in revised form 3 October 2010; accepted 27 March 2011
Available online 30 April 2011

Communicated by: Associate Editor Halime Paksoy

Abstract

Experiments were conducted to investigate the effectiveness of a porous manifold in the formation and maintenance of thermal stratification in a liquid storage tank. A thermal storage tank with a capacity of 315 L and a height-to-radius ratio of 4 was used for the experiment. The porous manifold used was made from rolling up a nylon screen into the shape of a tube. Stratification was observed at a Richardson number as low as 0.615. Flow visualization was also performed to confirm the effectiveness of the porous manifold in the promotion and maintenance of stable thermal stratification. From the results of flow visualization, one can conclude that a porous manifold is able to reduce the shear-induced mixing between fluids of different temperature, and thus is able to promote and maintain a stable stratification.

Keywords: Thermal storage tank; Thermal stratification; Porous manifold

1. Introduction

Separation of hot and cold fluids contained in a thermal storage tank may be desirable for many applications. This can be accomplished naturally or by the use of physical barriers. A natural stratification scheme employs carefully designed inlet diffuser, which yields evenly distributed flow with low velocity to promote the formation of thermocline. In contrast, physical barriers can be used to separate the warm and cold fluids. However, these would require additional devices to be installed in the tank and thus increase the cost and complexity of the system. Considerable research efforts have been devoted in the area of thermal storage. Particularly those initiated and sponsored by the International Energy Agency (IEA), for example, Task 26 Solar Combisystems and Task 32 Advanced Storage Concepts for Solar Thermal Systems in Low Energy Buildings, are documented and can found in the agency web site (Solar Heating & Cooling Programme, International Energy Agency (2003, 2008), Vogelsanger et al. 2007).

Destratification in thermal storage tank has been attributed mainly to plume entrainment and mixing produced by inlet flow (Hollands and Lightstone, 1989). It was shown by Gari and Loehrke (1982) that an inlet at the top of the tank was acceptable if the temperature of the water entering the tank was always beyond the temperature extremes of the stored water. However, severe mixing can occur if the temperature of the inlet water fluctuates below the temperature extremes of the stored water, a situation which is frequently encountered in solar energy storage systems due to the intermittent nature of solar radiation. To suppress the two adverse effects mentioned above, it was proposed by Loehrke et al. (1979) to use a porous shroud to contain the vertical inlet flow. The proposed porous shroud would produce a controlled buoyant jet which

* Corresponding author.
E-mail address: flai@ou.edu (F.C. Lai).

0038-092X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2011.03.024

Nomenclature

c_p	specific heat of fluid (kJ/kg K)
g	gravitational acceleration (m/s^2)
Gr	Grashof number, $Gr = g\beta(T_i–T_\infty)\ r_t^3/v_2$
h	heat transfer coefficient (W/m^2 K)
K	permeability of porous medium (m^2)
l	height of cylindrical tank (m)
L	dimensionless height of cylindrical tank, $L = l/r_t$
Pe	Peclet number, $Pe = Re{\cdot}Pr$
Pr	Prandtl number, $Pr = v/\alpha$
r	radial coordinate (m)
r_i	inner radius of porous tube (m)
r_{in}	radius of inlet manifold (m)
r_o	outer radius of porous tube (m)
r_t	radius of tank (m)
R	dimensionless distance in r-direction, $R = r/r_t$
Ra	Rayleigh number, $Ra = Gr{\cdot}Pr$
Re	Reynolds number, $Re = u_i\ r_t/v$
Ri	Richardson number, $Ri = Gr/Re_2$
R_{in}	dimensionless radius of inlet manifold, $R_{in} = r_{in}/r_t$
t	time (s)
t_{fil}	filling time, $t_{fil} = V_t/\dot{V}$ (s)
T	temperature (K)
T_i	inlet temperature (K)
$T_{initial}$	initial temperature (K)
T_{mix}	mixing tank temperature (K)
T_∞	ambient temperature (K)
ui	inlet velocity in z-direction (m/s)
$\dot{V}$	volumetric flow rate (ml/s)
Vt	volume of storage tank (ml)
z	axial coordinates (m)
Z	dimensionless distance in z-direction, $Z = z/r_t$
Z_1	dimensionless location of the leading edge of thermocline
Z_2	dimensionless location of the trailing edge of thermocline

Greek symbol

α	thermal diffusivity of fluid (m^2/s)
β	coefficient of volumetric expansion due to temperature change (1/K)
θ	dimensionless temperature, $\theta = (T–T_\infty)/(Ti–T_\infty)$
θ_{mix}	dimensionless mixing tank temperature
μ	dynamic viscosity of fluid (kg/m s)
v	kinematic viscosity of fluid (m^2/s)
ρ	density of fluid (kg/m^3)
τ	dimensionless time, $\tau = t/t_{fil}$

allows the incoming fluid to pass through warmer water in the upper region of the tank without mixing. To this end, a vertical porous manifold was introduced, which would reduce shear-induced mixing between fluids of different temperature. Two types of manifolds were constructed and tested, the rigid porous manifold (RPM) and the flexible porous manifold (FPM). Test results showed that both manifolds produced a temperature profile similar to that predicted for an ideal stratification. Much of this stratification was preserved during cycling (changes in the inlet condition). The follow-up studies by Davidson et al. (1994), Andersen et al. (2007, 2008) have all shown the effectiveness of porous manifold.

A numerical study conducted by Yee and Lai (2001) to predict the flow and temperature fields in a storage tank, indicated that a porous manifold with a low permeability had an adverse effect on the formation of thermal stratification at low Richardson numbers (i.e., at a higher flow rate for a given inlet temperature). It was suggested that a more permeable tube would produce better results. In this study, a full-scale storage tank that was used in the numerical study of Yee and Lai (2001) is actually constructed. The measurements of the temperature distribution and flow rate are used to evaluate the performance of a porous manifold on the formation and maintenance of thermal stratification under various inlet conditions. The porous manifold was made from rolling up a nylon netting, which is normally used in the building construction industry to hold insulation in sheet racks, into the shape of a tube. Clearly, this is one of the simplest and most economical ways to create a porous manifold. Although the manifold is somewhat rigid, it is flexible enough to satisfy the pressure-matching requirement by changing its area slightly. An inlet flow distributor was integrated with the porous manifold to reduce the vertical momentum of the incoming fluid. Flow visualization was also conducted to confirm the ability of the inlet distributor to diffuse axial momentum of flow under various inlet conditions and the effectiveness of the porous manifold in the suppression of plume entrainment and turbulent mixing.

2. Experimental setup

A schematic drawing of the experimental setup is shown in Fig. 1. The setup consists of three major parts: storage tank (with the porous manifold and inlet distributor), charging flow loop and data acquisition system.

2.1. Storage tank

The storage tank was fabricated from a cast acrylic tube of 1.22 m (48 in.) long and 0.61 m (24 in.) in outer diameter and 0.584 m (23 in.) in inner diameter. Two circular discs, which were cut from a Plexiglas sheet of 2.54 cm (1 in.)