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Performance of a rigid porous-tube stratification manifold in comparison to an inlet pipe

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ABSTRACT

Achieving thermal stratification of storage tanks has well documented advantages for increasing the efficiency and quality of delivered energy of solar heating systems. The present work presents experimental characterization of a porous tube manifold during charging of a water tank at 0.07 kg s^{-1}. Measurements of vertical temperature distributions are used to evaluate the dimensionless exergy efficiency of the manifold in comparison to a top-mounted inlet pipe and an inlet pipe with a diffuser. Particle image velocimetry measurements illustrate the fluid dynamic behavior of the three inlet configurations. Results demonstrate that the manifold is superior to the other inlet configurations studied. It releases the incoming flow at the level of neutral buoyancy, and prevents suction of tank fluid into the manifold at other vertical levels.

1. Introduction

Achieving thermal stratification of storage tanks has well documented advantages to increase the efficiency and quality of delivered energy of solar heating systems. Stratification of water storage tanks can increase the annual solar fraction of combined solar water/space heating systems (combi-systems) and solar hot water systems by 6–38% depending on the design and operating conditions of the system (Andersen and Furbo, 2007; Wuestling et al., 1985).

The design of the inlet to the tank has a profound impact on thermal stratification during charging. The major causes of mixing and destratification are jet mixing and plume entrainment (Hollands and Lightstone, 1989). Jet mixing is most prevalent during top charging when the fluid entering the tank is warmer than the fluid stored in the tank. For Richardson numbers (the ratio of the buoyancy to inertial forces) less than unity, the inlet jet penetrates deep into the tank and mixing is extensive. Jet mixing is reduced in lower flow systems (Hollands and Lightstone, 1989) and in tanks with large diameter inlet pipes or diffusers that slow the velocity of the fluid entering the tank. Plume entrainment occurs when the inlet fluid is cooler than the fluid stored at the top of the tank but warmer than the fluid stored at the bottom, referred to as intermediate charging. In this situation, a stratification manifold is beneficial. An effective manifold releases the inlet fluid to the tank at the vertical position where the temperatures are equal (the level of neutral buoyancy) and prevents flow into or out of the manifold elsewhere.

Designing a manifold for low Richardson numbers and variable operating conditions has proven challenging. Over the past 30 years, a number of distribution manifolds have been proposed. The designs include the rigid porous manifold (Brown and Lai, 2011; Wang and Davidson, 2015a), the rigid porous manifold with vertical hydraulic resistance elements (Davidson and Adams, 1994; Gari and Loehrke, 1982; Loehrke et al., 1978; Sharp and Loehrke, 1979), flexible porous manifolds (Andersen et al., 2007; Davidson and Adams, 1994; Gari and Loehrke, 1982; Wang and Davidson, 2015b), and the rigid pipe with check valves (Andersen et al., 2008; Shah et al., 2005). Arguably, the simplest of these designs is a rigid porous-tube manifold. The rigidity of the tube prevents the manifold from collapse, which would encourage suction of tank fluid into the manifold because of the Bernoulli effect in a flexible porous channel (Wang and Davidson, 2015b). The porous wall acts as a barrier to reduce shear between the incoming flow and the surrounding tank fluid and allows fluid to flow from the tube at the proper vertical position. The tube can be attached to an inlet diffuser to slow the flow and raise the Richardson number. The present authors applied results of a computational fluid dynamic model of such a manifold to develop design guidelines (Wang and Davidson, 2015a). The diameter of the tube should be large enough to slow the average velocity into the tube, U, to achieve a Richardson number of 100 or higher. The Richardson number is defined as

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Nomenclature

A	cross section area of the tank (m^2)
c_p	specific heat of water (kJ/kg/K)
D	diameter (m)
e_x	specific exergy (J/kg)
E	total exergy in the tank (J)
E_x^*	dimensionless exergy efficiency
g	gravitational constant (m^2/s)
h	specific enthalpy (J/kg)
k	thermal conductivity (W/m/K)
K	permeability of the porous manifold (m^2)
$\tilde{K}$	dimensionless permeability, $\tilde{K} = 16KL\dot{m}/\pi\mu\delta D_i^3$
L	tank height (m)
M	relative entrainment rate
$\dot{m}$	mass flow rate of inlet flow (kg/s)
p	pressure (Pa)
Δp	pressure drop (Pa)
r	radial coordinate (m)
Re_D	Reynolds number, $Re_D = \rho UD/\mu$
Ri_L	Richardson number, $Ri_L = gL\beta(T_H - T_C)/U^2$
s	entropy (J/K)
t	time (s)
T	temperature (°C)
U	average velocity at inlet, $U = 4\dot{m}/\pi D_i^2\rho$
u	radial velocity (m/s)
u_D	Darcy velocity (m/s)
w	vertical velocity (m/s)
z	vertical coordinate (m)

Greek letters

β	thermal expansion coefficient 1/°C
δ	thickness (m)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)

Subscripts

C	cool temperature
Diffuser	diffuser
e	entrainment or edge of plume
H	hot temperature
i	inner diameter
in	inlet
L	tank height
Manifold	manifold
mix	mixed state
o	reference state or the outer diameter
out	outlet
pipe	inlet pipe
r	radial direction
st	stratified state
up	upper boundary of thermocline

$$Ri_L = \frac{gL\beta(T_H - T_C)}{U^2} \qquad (1)$$

The relevant scales are the height of the tank, L, and the average inlet velocity, U. For selection of the porosity and pore structure of the tube, the key design parameter is the dimensionless permeability $\tilde{K}$ (Wang and Davidson, 2015a, 2015b), defined by Eq. (2), which is the ratio of the radial pressure drop and the vertical pressure drop in the tube.

$$\tilde{K} = \frac{16L\dot{m}}{\pi\mu D_i^3}\frac{K}{\delta} \qquad (2)$$

Here, K is the permeability of the porous tube, δ is the thickness of the tube wall, and D_i is the inner diameter of the tube. Fig. 1 shows the recommended design values of $\tilde{K}$ for $100 \le Ri_L \le 1000$ for top and intermediate charging (Wang and Davidson, 2015a). For intermediate charging, the optimum $\tilde{K}$ ensures fluid flows into the tank at the height of neutral buoyancy and eliminates suction into the manifold. A higher $\tilde{K}$ will allow suction of warmer tank fluid stored at the top of the tank into the manifold, whereas a lower $\tilde{K}$ will allow release of the inlet fluid over a larger region, both above and below the height of neutral buoyancy. In the limit, if $\tilde{K}$ is too low, the manifold will act as a diffuser releasing fluid over the entire height of the tank. For top charging, the recommended $\tilde{K}$ will ensure release of fluid in the top 20% of the tank. We recommend a value of $\tilde{K}$ that falls between the two curves to balance performance for top and intermediate charging (Wang and Davidson, 2015b). The difference between the recommended values of $\tilde{K}$ becomes smaller as Richardson number is increased.

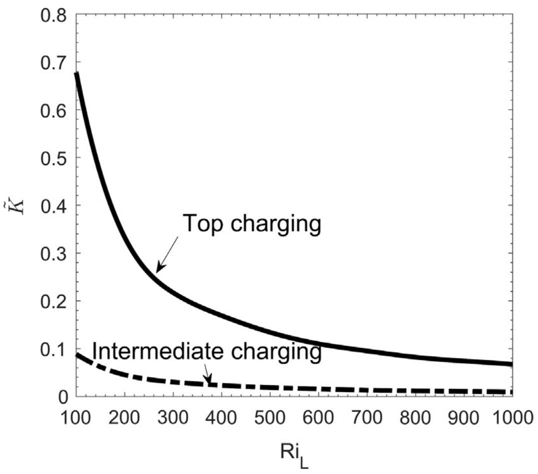

Fig. 1. Guideline for selection of the dimensionless permeability versus Richardson number (Wang and Davidson, 2015a).

In the present work, we extend our prior computational work to design and demonstration of a porous-tube manifold for both top and intermediate charging of a water storage tank. The performance of the manifold is compared to that of a top-mounted inlet pipe, and an inlet pipe with diffuser. The conventional storage tank used in the US for water heating has inlet ports on the top of the tank. Thus, we selected this configuration as a baseline for comparison. The diffuser is a second option considered to prove that the porous tube manifold, which also has a diffuser, performs better than a diffuser alone. A dimensionless exergy efficiency based on measured temperature distributions quantifies stratification. The fluid dynamic behavior, specifically plume entrainment and suction into the manifold, is interpreted from particle image velocimetry (PIV) measurements of the velocity field.

2. Experimental method

2.1. Inlet configurations

Fig. 2 shows the three inlet configurations. The inlet pipe (Fig. 2 (a)) is a schedule 40 PVC pipe with D_i = 15.8 mm and D_o = 21.3 mm,