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Thermocline Movement Dynamics and Thermocline Growth in Stratified Tanks for Heat Storage

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An experimental and numerical study using a scale model of an industrial stratified tank (aspect ratio 3.5) and a Perspex tank (aspect ratio 8.2) are reported. The affect of thermocline rise or fall rate, inlet flow rates, tank aspect ratio and wall heat loss on the degree of stratification are studied. A new measure of stratification is proposed to compare results. Four fundamental flow and heat transfer mechanisms are shown to contribute to thermocline growth and loss of tank stratification. Findings are relevant to industrial stratified tanks which require thermocline re-establishment on a regular basis.

1. Introduction

Stratified tanks and Heat Recovery Loops (HRL) are useful for integrating process heat between non-continuous and semi-continuous industrial processes. Liquid of high and low temperature is stored within the same tank to provide buffer and storage for variations in HRL heating and cooling loads. Load imbalance causes movement of the thermocline up and down the tank which results in degradation of the thermocline and ultimately loss of useable storage capacity. Understanding how thermocline movement affects the rate of thermocline degradation is therefore important and of value to the design and management of HRLs.

Water is the most widely used medium for sensible heat storage in stratified tanks. The method exploits the high thermal capacity of water and the natural buoyancy effect of water at different temperatures. A hot zone of lower density forms in the top of the tank and a cold zone of higher density in the bottom (Figure 1). In between a region of steep temperature gradient is formed, called the thermocline, which acts like a barrier.

A high degree of temperature stratification is required for the tank to be usable in a HRL. Numerous stratification performance measures have been proposed and no method is widely accepted (Sliwinski, 1978; Abdoly and Rapp, 1982; Adams, 1993; Rosen, 2001; Zurigat and Ghajar, 2002; Haller and Streicher, 2009). The ideal case is when the hot and cold regions are completely separate and the thermocline temperature gradient is infinite. Comparing the actual temperature profile with the ideal defines a new dimensionless number called the Percentage of Ideal Case (*PIC*) (Equation 1), where A_1 and A_2 represent loss of stratification in the cold zone and hot zone, H is the

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height of the storage tank, *T(h)* is the fluid temperature at height *h*, *h** is the non-dimensional height and *T** is the non-dimensional temperature.

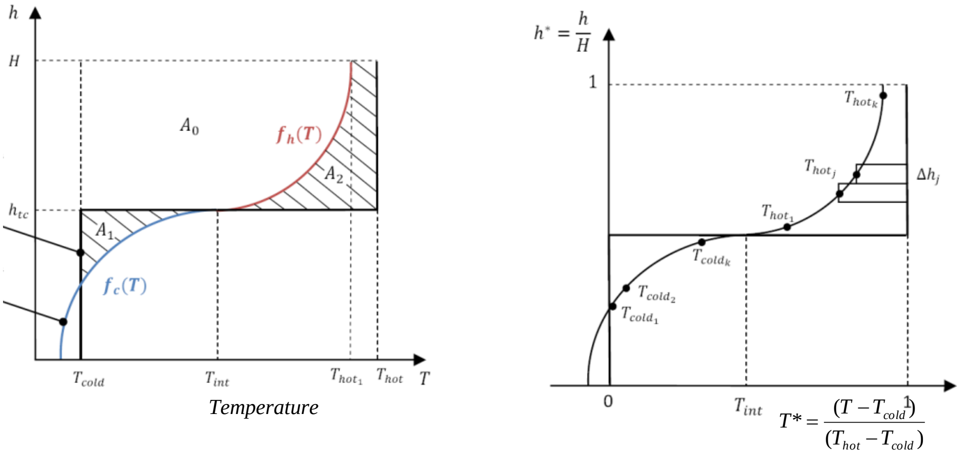


Figure 1: Temperature profile and non-dimensional temperature profile of a stratified tank.

$$PIC = 1 - \frac{A_1 + A_2}{0.5} = 1 - \frac{\sum_{j=1}^{k} \Delta h_j (1 - T_{hot\,j}) + \sum_{j=1}^{k} \Delta h_j (T_{cold\,j} - 0)}{0.5} \tag{1}$$

The tank is perfectly stratified when *PIC=1*, is completely mixed with a uniform temperature or completely cooled down to T_{cold} or lower when *PCI=0* and the tank is in normal operating mode when *0<PIC<1*. Loss of stratification is caused by mixing within the fluid layers, heat loss to the ambient surroundings, diffusion across the thermocline and heat transfer via the wall from high to low temperature regions. The *PIC* number provides a means to compare the contributions of each mechanism.

2. Experimental and CFD studies

Laboratory and 3D CFD studies of two tanks (Table 1) were undertaken to determine the causes of stratification loss in a stratified tank. Temperature profiles were measured using T-type thermocouples and CFD temperature contours were derived directly from the CFD results. Laboratory studies used the setup illustrated in Figure 2.

Table 1 Dimensions of tanks investigated in experimental and CFD studies.

Tanks	*Perspex*	*Stainless*
Diameter [mm]	*100*	*360*
Wall thickness [mm]	*5*	*1.5*
Length [mm]	*820*	*1276*
Aspect ratio (length/diameter)	*8.2*	*3.5*
Inlet and outlet port diameter [mm]	*10*	*21*

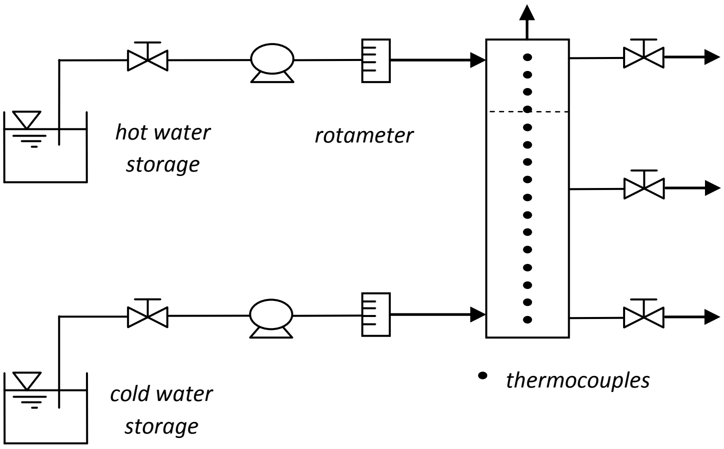


Figure 2: Schematic of experimental system.

Four cases were investigated. *(1) Stationary mode:* A near perfect thermocline was first established in each tank and the loss of stratification over time was measured with no inlet and outlet flow (static mode), with and without insulation. For comparison CFD models were developed for the well insulated tank case (adiabatic model) and the no insulation case (constant external wall heat transfer model). *(2) Charging the Tank* is the process used in industry to establish two temperature zones in a stratified tank. The tank was initially full of cold water and was then replaced with hot water from the top while cold water was withdrawn from the bottom. The effect of inlet and outlet flow rate on thermal stratification was studied. *(3) Up and Down Thermocline Movement* was studied by moving the thermocline height from 50 % to 80 % to 20 % and back to 50% at different flow rates. Hot and cold waters flows in and out of the tank were switched to facilitate the different thermocline movements. *(4) Inlet Flow Mixing Effects* on stratification was studied by establishing a near perfect thermocline at 50, 60, 70 and 80 % height and varying the flow rates in and out of the top of the tank.

A 3D CFD mesh consisting of 169,884 elements (Perpsex tank) and 489,951 elements (SS tank) was used with a time step of 0.5 seconds. Mesh independence tests were performed on five 3D meshes of different resolutions and time-step-dependence tests were also performed. A laminar model was used over a turbulence model, as others researchers have done to solve similar flow problems (Ievers, 2009).

3. Results and Discussion

Temperature profiles, CFD temperature contour plots and the *PIC* number are used to summarise and compare results.

1.1 3.1 Static Mode

CFD and laboratory studies are in good agreement (Figure 3). Heat transfer by diffusion is initially significant but over time heat loss to the environment from the hot top layer becomes the predominant effect. Insulation reduces heat loss from the top layer and a more uniform temperature distribution is maintained in the hot zone over time.

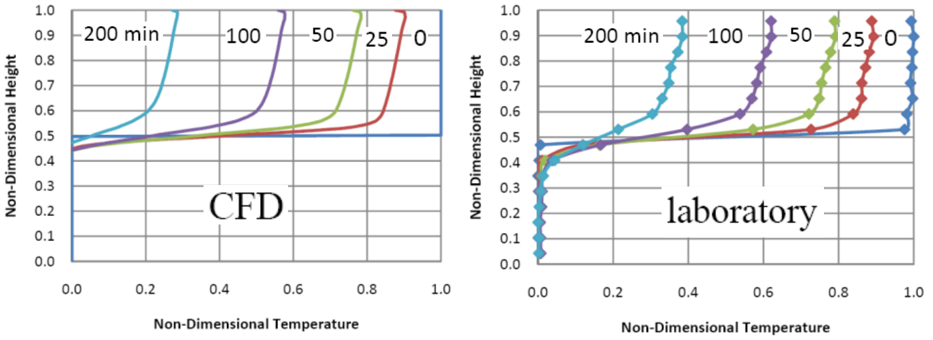


Figure 3: Non-dimensional transient temperature profiles of the static mode for the Perspex size tank without insulation (a) CFD (b) laboratory.

1.2 3.2 Thermocline charging

CFD temperature contours for the Perspex size tank being charged with hot water at two different flow rates are presented in Figure 4. In each case three layers develop in the tank, a hot zone, a cold zone and a thermocline region of intermediate temperature.

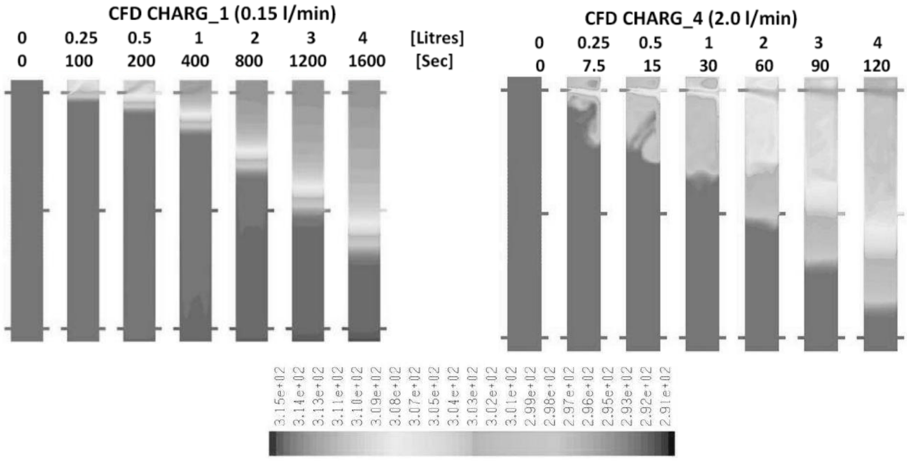
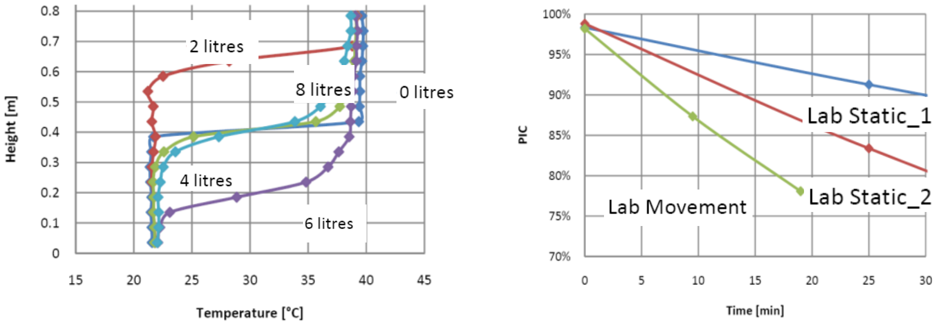


Figure 4: CFD temperature contours of Perspex tank at two charge rates.

With increasing inlet flow rate the upper layer is of lower temperature than the inlet temperature and the thickness of the thermocline region is increasing, indicating a larger degree of mixing. The inlet jet with the lowest flow rate (CFD Charg_1) lifts up due to buoyancy forces. A region with mixed water temperature develops which is pushed down by incoming fluid. Above the jet a temperature region with an almost uniform temperature equal to the inlet stream temperature develops. The high inlet flow stream (CFD Charg_4) flows almost straight. The inlet jet with a considerable momentum strikes the back of the tank and disperses the hot fluid into a large area. Consequently the tank becomes more mixed and the temperature in the top layer is cooler than that observed in the hot inlet.

1.3 3.3 Up and Down Thermocline Movement

Results for one set of data are presented in Figure 5a. A near perfect thermocline started at 0.4 m (50% height) and rose to 0.65 m (80 % height) as 2 L of cold water was added from the bottom of the tank. Thermocline movement was then reversed and returned to 50 % by adding 2 L of hot water from the top (4 L total). A further 2 L of hot (6 L total) lowered the thermocline to 0.2 m (25 % height), after which the thermocline was again reversed back to 50 % with another 2 L of cold (8 L total).



(a) (b)

Figure 5: Up and down thermocline movement in the Perspex tank and PIC number development for movement and static modes, in and out flow rate of 0.4 lpm.

The thermocline thickness increased with time and this is confirmed by the PIC number also decreasing with time (Figure 5b). Thermocline movement gave enhanced loss of stratification compared to the static mode 1 (insulated tank) and static mode 2 (uninsulated tank). Extra loss arises due to heat transfer from high temperature regions to the low temperature regions via the tank wall inducing localized buoyancy driven currents. When the thermocline level moves up cold water comes in contact with the hot wall, heats up, becomes of lower density and rises near the wall. When the thermocline moves down the reverse happens. Hot water close to the wall cools down, becomes of higher density and falls near the wall. The degradation of the thermocline is therefore affected by the rate of thermocline movement up and down, the conducting material of the tank and the wetted perimeter of the tank per unit volume. The stainless steel tank gave less stratification loss for similar thermocline movement rates due to a much lower wetted perimeter per unit volume compared to the Perspex tank, even though the wall thermal conduction properties were higher.

1.4 3.4 Inlet Flow Mixing Effects on Thermocline Stability

Inlet flow effects are illustrated by temperatures profiles in Figure 6 and velocity vector contours in Figure 7 for the insulated stainless steel tank.

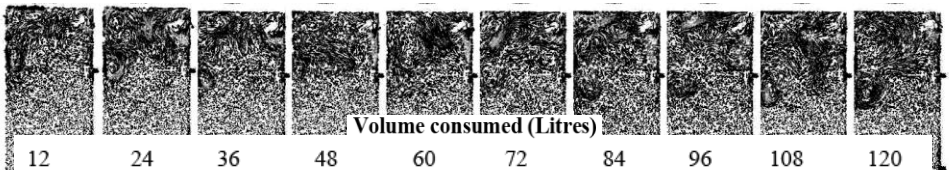


Figure 6: CFD velocity vector contours of the top half of the stainless steel size tank. Hot inlet and outlet flow 6 LPM (Re = 6063).

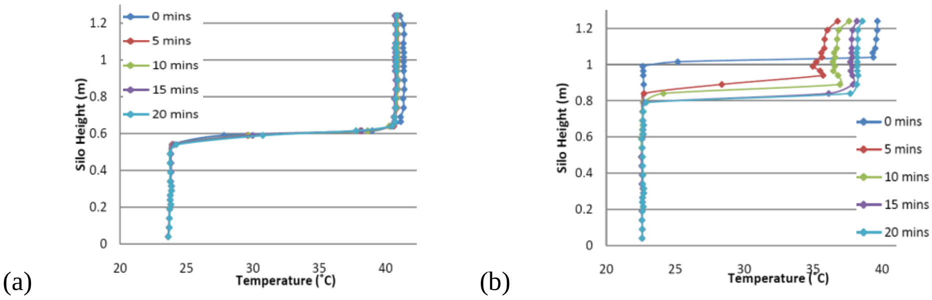


Figure 7: Effect of hot inlet and outlet flow (Re=6063) on tank stratification for the insulated stainless steel tank. Initial thermocline height (a) 50 %, (b) 80 %.

Inlet flow mixing can expand the hot zone and lower the average hot temperature when the thermocline is near 80% of tank height even when Reynolds number is low. Thermocline height should therefore be restricted from getting within 20% of the inlet ports of the tank to minimise loss of stratification due to the inlet flow mixing mechanism.

4. Conclusions

Loss of stratification in stratified tanks is caused by four main mechanisms. Where the thermocline is near perfect diffusion heat transfer across the fluid lays initially dominants. Where a tank is uninsulated heat loss to the environment from the hot region increases the fluid density near the wall and generates buoyancy induced currents and thermal mixing. Thermocline movement also creates buoyancy induced currents near the wall as cold or hot fluid comes in contact with wall regions of different temperature. Thermocline levels within 20% of inlet ports also experience flow induced mixing even at low Reynolds numbers of 6000.

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