Thermocline Management of Stratified Tanks for Heat Storage

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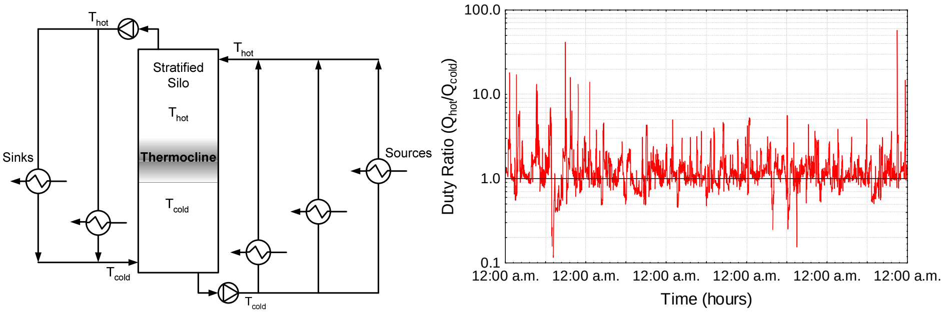
Stratified tanks are useful for maximising the thermal energy efficiency of non-continuous and semi-continuous processes. Liquid at two or more dissimilar temperatures is stored within the same tank to provide a buffer for variations in heating and cooling loads. Control of the thermocline between the hot and cold fluid regions is needed to minimise thermocline growth and maximise operation of the storage tank. An experimental programme using a scale model of an industrial stratified tank (aspect ratio 3.5) and Perspex tank (aspect ratio 8.2) is reported. The behaviour and growth of the hot-cold thermocline under various operating conditions is presented. A siphoning method to re-establish the thermocline without interrupting the use of the tank is tested. Siphoning of the thermocline region from either 20%, 50% or 80% of the tank height is an effective strategy for uninterrupted interface re-establishment. However, the rate and position of siphoning and the load balance of the exit streams are critical variables for minimising the time for effective re-establishment of the two temperature zones.

Introduction

Thermal Energy Storage (TES) systems are useful for maximising the thermal energy efficiency of non-continuous and semi-continuous processes. During times of low thermal demand excess thermal energy is stored in large insulated tanks for use at a later time. Storage can be accommodated with high specific heat fluids like water, or with phase change materials which take advantage of latent heat. TES systems can operate for both hot and cold storage on a charge-hold-discharge cycle or in a continuous mode where hot and cold fluid are added and removed from a stratified tank simultaneously. One common example is the storing of chilled water in large tanks during times of low demand and/or costs to reduce capacity requirements and operating costs on refrigeration plants (Zurigat & Ghajar, 2002). Another example is storing hot and cold water simultaneously in a stratified tank as part of a heat recovery loop of a semi-continuous food processing site (Fig 1). The demand for heat sources and heat sinks is variable and the stratified tank acts as a buffer to accommodate demand variations.

TES stratified tanks are able to operate effectively by exploiting the density difference of a single fluid at different temperatures. A region of higher temperature fluid (lower density) forms at the top of the tank and a region of lower temperature fluid (higher density) forms at the bottom. An intermediate or thermocline region forms in the middle and spans the temperature range. Stratification is enhanced by increasing the temperature difference between the fluid regions and through design of tank parameters such as aspect ratio, inlet/outlet port dimensions and inlet diffuser plates (Bahnfleth & Musser, 1998). Stratification is reduced through fluid mixing caused by natural and forced convection and through thermocline movement resulting from unbalanced heating and cooling loads.



(a) *(b)*

Figure 1. Industrial heating recovery loop (a) with simultaneous storage of hot and cold water in a stratified silo for smoothing variable heating and cooling duties (b).

The position of the thermocline can move up and down significantly within the stratified tank in response to changes in the heating and cooling loads (Fig. 2). Production rate changes, cleaning cycle interruptions or different product lines not operating can all cause heating and cool load variations. Thermocline movement speeds up the loss of stratification in the tank and ultimately results in the heat recovery loop being shut to enable the hot and cold fluid regions to be re-established in the tank. The temporary shut can be very costly in both time and interruption to the process. A re-establishment method that does not require shutting the recovery loop would therefore be useful for industry and is the focus of this paper.

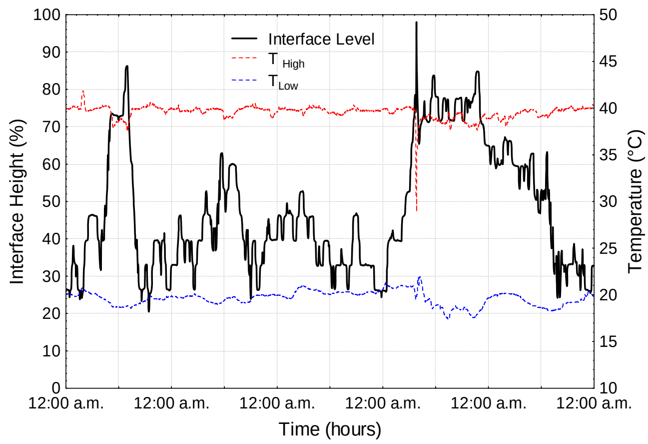


Figure 2. Variation in stratified tank thermocline level (interfacial height) for a semi-continuous food processing plant (Atkins et al, 2008).

Table 1. Dimensions of laboratory tanks

Tank type	Diameter, D (mm)	Length, L (mm)	L/D	Inlet & outlet port diameters (mm)	Thermocouple spacing
Perspex	100	818	8.18	10	80
Stainless steel	362	1268	3.5	20	50

Experimental Setup

Two laboratory tanks were constructed to study the stratification of water at various temperatures and inlet and outlet flow conditions, and to trial thermocline re-establishment methods by siphoning. The characteristics of the laboratory tanks are summarised in Table 1. Inlet and outlet ports were located at the top and bottom of each tank. Additional outlet ports were also placed in the middle of the tanks and at 80 and 20 percent of the height for the stainless steel tank to allow for siphoning of the thermocline. Type K thermocouples, attached to data loggers, were mounted vertically up the tanks, and inlet and outlet streams were independently controlled using VSD pumps for each stream. Stratification was established by filling the tank with cold water and then introducing hot water through the hot inlet while allowing the cold water to drain out of the cold outlet at the bottom of the tank. Once the thermocline had been established and set at the desired level, thermocline degradation experiments were conducted followed by thermocline re-establishment experiments. Tank thermocline characteristics are defined using the variables illustrated in Figure 3.

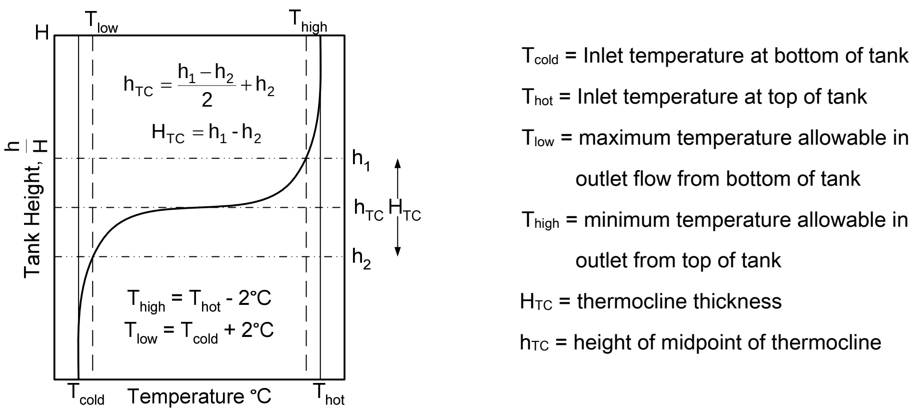


Figure 3. Illustration of variables used to describe a thermocline in a stratified tank.

Results and Discussion

1.1 Thermocline degradation

The combined effect of thermal diffusion, heat loss via the tank walls and inlet flow induced mixing was quantified by establishing an interface and allowing the thermocline to degrade over time. Typical results for the non insulated stainless steel tank are shown in Figure 4, without (Fig. 4a) and with (Fig. 4b) flows from the tank.

The effects of heat conduction are evident in Fig. 4a as the cold water layers near the interface gradually rise in temperature, while the hot layers above the interface decrease in temperature towards the ambient air temperature of 15^{o}C. A far greater decrease in the hot layer temperatures (compared to the cold increase) shows that a significant amount of stored heat is lost to the surrounding environment, as hot water cools against the tank wall, and heat is lost to the surroundings. Flow into and out of the tank significantly increases the rate of heat loss to the surroundings and the rate of degradation of the stratified layers. For example (Fig. 4b) after 240 minutes 75% of the tank is below 17^{o}C, compared to the no flow case (Fig. 4a) where after the same time the tank is still highly stratified.

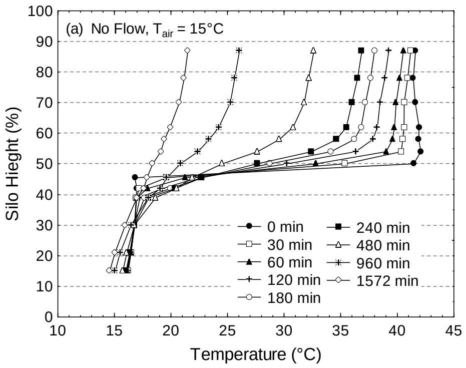


Figure 4. Thermocline degradation over time (a) no flow and (b) with 0.85 LPM flow in and out, non insulated stainless steel tank, initial thermocline height 50%, ambient air temperature 15^{o}C.

These results confirm that thermal diffusion makes a relatively minor contribution to thermocline degradation while fluid mixing due to eddy currents and convection heat transfer and is much more important (Zurigat & Ghajar, 2002). Convective currents are created within the tank due to the vertical temperature gradient along the tank wall, which cause mixing of hot and cold fluid in the region of the interface near the wall and are responsible for a significant amount of the degradation in this case. Flow into and out of the tank at the hot and cold ports also contributes to the establishment of convective current circulation which in turn speeds up thermocline degradation.

1.2 Thermocline re-establishment

Trials were conducted to investigate the feasibility of removing the thermocline region from a stratified tank that is still in operation. Figure 5 shows how a clear interface can successfully be produced from a well mixed tank with the aid of a siphon. The 0 minute line shows that the tank originally contained water between 30°C and 37°C. The hot outlet and cold outlet flow rates were kept equal and slowly lowered, and at the same time water was removed from the midpoint of the tank by siphoning at the rate of 0.7 L/min. Immediately the thermocline region in the tank decreased in size, and continued to narrow as more water was removed from the middle of the tank. The results show that the thermocline was reduced to less than a 10 percent of the tank height and remained in the middle of the tank. Stratification of the tank was achieved after removing 90 percent equivalent volume of the tank with both the hot and cold regions of the tank being established at the desired temperatures. V_s and V_t are the volume of fluid siphoned and volume of the tank respectively.

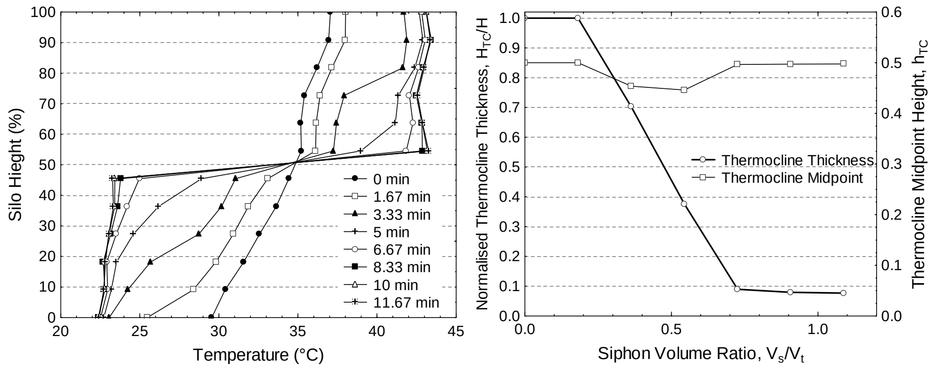


Figure 5. Interface re-establishment with siphoning from 50% height, perspex tank, siphon rate 0.7LPM.

Similar data are presented in Figures 6 and 7 for the stainless steel tank with siphoning rates of 3.4 LPM and 1.14 LPM respectively and a siphoning position of 50 percent. Tests were run with the initial thermocline below (Fig 6) and above (Fig 7) the siphon position and with the hot inlet stream greater than the cold inlet stream (Fig 7).

It can be observed in Figure 6 that after siphoning commenced the thermocline quickly narrowed and the midpoint of the thermocline increased from 35 to 50 percent height as the cold zone expanded to fill the lower half of the tank. Siphoning from the middle of the tank preferentially removed hot water from the top of the thermocline zone and allowed cold water filling from the bottom to take its place. Some fluid mixing may have occurred but based on the volume removed to re-establish a narrow thermocline it was close to 100 percent removal efficiency. The reduction of the thermocline thickness and movement of the thermocline height with volume removed is illustrated in Figure 6b.

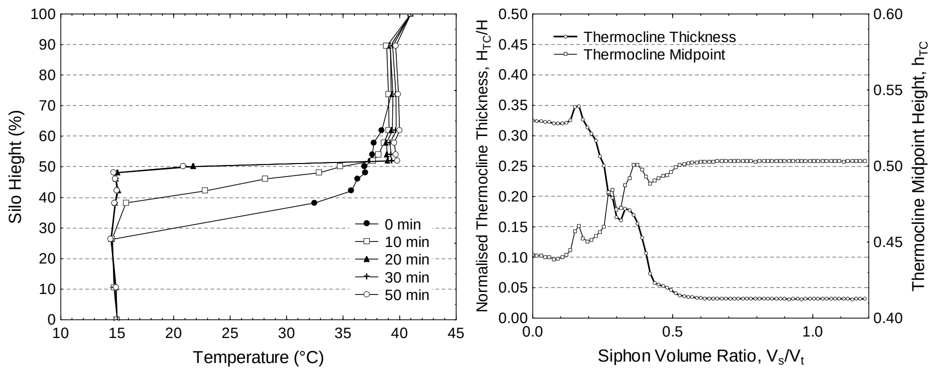


Figure 6. Interface re-establishment with siphoning from 50% height, stainless tank, siphon rate 3.9LPM.

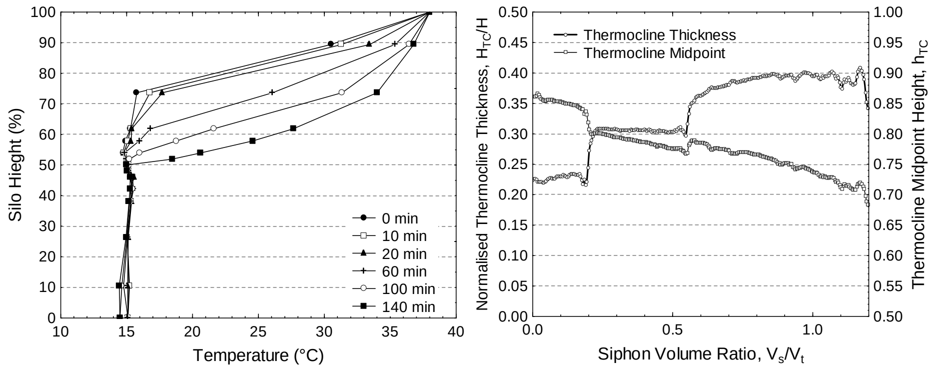


Figure 7. Interface re-establishment with siphoning from 50% height, stainless tank, siphon rate 1.14LPM.

In Figure 7 the thermocline does not narrow with siphoning but expands downward towards the siphon outlet at 50 percent due to the out of balanced in-flow the thermocline expands downward towards the siphon outlet at 50 percent. This effect is more clearly illustrated in Figure 7b. In-flow balance is clearly an important consideration when using the siphon method to re-establish the thermocline. Work is continuing in this area as part of a more comprehensive research programme into the role of stratified tanks and heat recovery loops in the New Zealand Dairy Industry.

Conclusions

The stratification of a thermal storage tank is an important factor in the operation of some industrial heat recovery systems. Degradation of the thermocline is caused by thermal diffusion across the interface, heat losses, heat conduction along the wall, and fluid mixing. The level of mixing is affected by the flows in and out of the tank and it was found that stratification degraded faster as the flow rates increased. The stratification could be re-established while still operating the tank in the usual manner by siphoning the mixed thermocline region from the tank. This method could be used to eliminate the need to flush industrial stratified tanks by allowing the thermocline to be re-established while still operating.

References

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