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ANALYSIS OF A MODULAR THERMAL STORAGE FOR SOLAR HEATING SYSTEMS

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ABSTRACT

The thermal performance of a multi-tank water storage was investigated by experiment and computer simulation. The unit studied was comprised of three 270 L storage tanks connected in parallel or series and was charged through side-arm, natural convection heat exchangers installed on each of the tanks. Laboratory tests were conducted on a specially instrumented prototype that allowed the storages to be evaluated in terms of temperature stratification, heat transfer and energy storage rates. Computer modeling was verified by comparison with these laboratory measurements. Finally, a series connected multi-unit storage was compared with a comparable single-tank system in a multi-family solar domestic hot water system application.

INTRODUCTION

A key component in a solar thermal system is the thermal storage unit. In small systems used for residential hot water production, standard hot water storages are often used because they are readily available at low cost. As the size of the solar load increases, however, storage volumes are usually increased in proportion. Larger storage tanks are available but are often expensive and may be physically too large to move into existing buildings.

An alternative to using a single tank storage configuration is to apply a modular approach based on the use of multiple storage tanks that are "plumbed" into a single thermal unit. In many cases, multiple small storage tanks may be easier to transport and assemble on site than a single storage unit. As well, many desirable features found in a single tank storage may be retained in a multi-tank system including large storage capacity, thermal stratification and freeze protection.

The operation of a multi-tank storage that utilized immersed-coil heat exchangers located at the top and bottom of each tank has been described by Mather et al. (Mather et al., 2002). The individual tanks were charged and discharged in a sequential, counter flow configuration. This arrangement was shown to have a number of attractive features, including "thermal-diode" operation and sequential stratification, however, it required the fabrication of custom tanks and therefore has not been widely used.

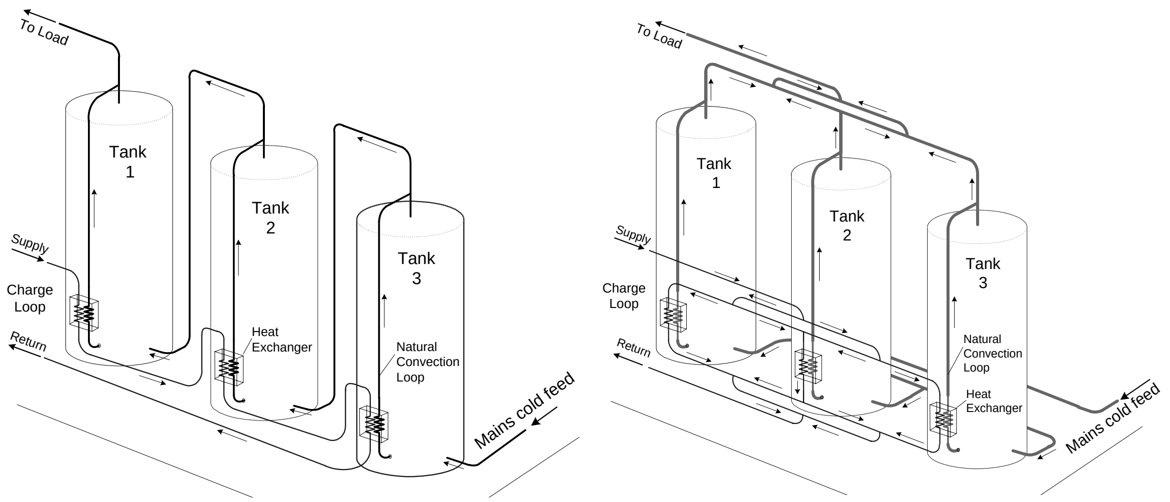
Consequently, this paper investigates the performance of a multi-tank thermal storage incorporating natural convection heat exchangers (NCHE's). The design is based on a commercially available, solar domestic hot water (SDHW) system that uses a side-arm NCHE coupled to a standard electric hot water heater/storage. When used in the SDHW system, the electric elements in the tank are disabled and "mains" water is preheated prior to feeding into a downstream auxiliary heater.

Both parallel and series configurations of the storage system were studied as described below. In addition, a computer model of both configurations (parallel and series) was developed using Version 15 of the TRNSYS simulation software (TRNSYS, 2000). The computer model was refined based on a comparison with measurements conducted in the laboratory and finally, the performance of a similar unit was modeled for a medium sized, multi-family residential application.

Description of the Storage Systems Studied

The systems studied consisted of three individual storage tanks, each fitted with separate sidearm heat exchange loops, Fig. 1. Charging of the multi-unit thermal storage is accomplished through a single, anti-freeze circulation loop, i.e., heat from the solar collectors is transported to the storage system by the circulation of a water-glycol mixture. Each storage tank was fitted with an individual heat exchanger to allow the transfer of solar heat during charging.

The heat exchangers evaluated were commercially available, compact, brazed-plate units consisting of 20 plates each (10 channels on the cold side and 9 channels on the hot side). The heat exchangers were located at the bottom of the side-arm circulation loops that connected the bottom to the top of each tank. Storage water is circulated through the heat exchangers by buoyancy induced, natural convection flow (Lin et al., 2000). The specifications of the storage tanks and heat exchangers used in the multi-tank system are summarized in Table 1.



a) b)

Fig. 1. Multi-tank storage configurations studied: a) series-connected for charge and discharge, and b) parallel-connected for charge and discharge.

Significant research has been conducted on NCHE systems to arrive at suitable configurations and these were used as the basis for the multi-tank system studied (Cruickshank et al., 2006a). A specialized test apparatus was constructed, Fig. 2, for the study (Cruickshank et al., 2006b) that permitted both the parallel and series flow arrangements to be rapidly configured through valve positioning. This also allowed the same major components, (e.g., heat exchangers, storage tanks, charge loop, etc.) to be used for both configurations, thereby reducing cost and potential sources of uncertainty. A central electric heater was used to simulate the heat input to the charge loop.

Table 1.
Specifications of storage system

Storage Tanks	- Three identical (residential) electric hot water heaters (electric elements disabled), 270 L each. - Steel (glass lined), insulated with 2 inch (0.05 m) thick fiberglass - Height = 1.5 m, diameter = 0.55 m - U = 5 kJ/hr m^2 ^{o}C
Heat Exchangers / Natural Convection Loops	- Three stainless steel, compact, brazed-plate heat exchangers (effective heat transfer area, 0.396 m^2, 20 plates each) - UA = 160-220 W/^{o}C each - Insulated, height = 0.31 m - Natural convection loop of nominal 0.5 inch (0.0125 m) copper pipe from heat exchanger to top of tank.

In the parallel arrangement, the flow from the charge loop was split in three, i.e., one-third of the flow was directed to each heat exchanger. The plumbing arrangement used was selected after multiple attempts to arrive at a balance flow (Cruickshank et al, 2006a). Consequently, both the charge-loop and the load-side discharge loops were configured in parallel through a branched header, Fig. 1 (b).

In the series arrangement, the individual thermal storages and related natural convection heat exchangers were connected in series such that the flow exiting the first heat exchanger enters the subsequent "downstream" heat exchanger. On the load side, each tank was also connected in a series, counter-flow configuration with respect to the charge flow direction.

Fig. 2. Experimental test apparatus (prior to insulating).

BACKGROUND THEORY

Multiple tank thermal storages can be connected in series or parallel arrangements. In addition, to prevent freezing, a heat exchanger is usually placed between the solar collector charge-circuit and the thermal storage (Fig. 3).

Each of these storage configurations has unique characteristics, e.g., the parallel configuration, Fig. 3(a), can function in a similar fashion to a single tank of equal height, while the series configuration can operate like a single tank of twice the height. In addition, if carefully configured, it is possible to develop significant thermal stratification, from high temperature to low temperature in both arrangements (Cruickshank et al., 2006a).

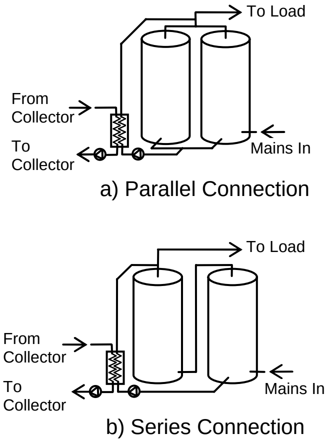


Fig. 3. Parallel and series connected hot water storage tanks charged through a collector-side heat exchanger.

In the series-connected configuration, the tanks will sequentially stratify, i.e., the left-hand tank will stratify at higher temperatures than the right-hand tank during charging. Stratification in storages has been shown to significantly increase the thermal performance in solar heating systems by allowing cool fluid to circulate to the solar collectors while maintaining hot-water at the top of the storage for distribution to the load (Hollands et al., 1989). In the parallel configuration both tanks will have the same temperature profile if the flow through the tanks is distributed equally, i.e., balanced.

Natural Convection Heat Exchanger Performance

For this study, it was decided to investigate storage tanks fitted with side-arm charging circuits and natural convection heat exchangers (NCHE's). This configuration has the advantage of allowing the use of inexpensive standard hot water tanks. The performance of NCHE's has been extensively studied (Hollands et al., 1989, Lin et al., 2000, and Cruickshank et al., 2006c). The flow on the storage side is driven by temperature-dependent buoyancy forces that are controlled by the temperature distribution of the heat exchange loop and the storage tank. As the thermal storage temperature approaches the temperature of the heat exchange loop, both the net hydrostatic pressure and natural convection flowrate decrease to maintain equilibrium conditions.

To account for these performance dependencies, a set of modified performance equations was proposed to better reflect their operational characteristics (Fraser et al., 1995). These "modified" performance parameters are based on the pumped, collector-side capacitance rate, $(\dot{m}\,c_p)_c$, rather than the minimum capacitance rate as calculated by the conventional indices. Referring to Fig. 4, the modified performance indices are defined as the following:

the modified effectiveness,
$$\varepsilon_{\text{mod}} = \frac{Q_{actual}}{Q_c} = \frac{(\dot{m}c_p)_s(T_{so}-T_{si})}{(\dot{m}c_p)_c(T_{ci}-T_{si})} \quad (1)$$

the modified capacity ratio,
$$C_{r\,\text{mod}} = \frac{(\dot{m}c_p)_s}{(\dot{m}c_p)_c} \quad (2)$$

where T_{si}, T_{so}, and T_{ci}, T_{co} are the inlet and outlet fluid temperatures of the collector side and storage side flows, respectively, and $(\dot{m}\,c_p)_s$ and $(\dot{m}\,c_p)_c$ are the storage and collector side heat capacitance rates, respectively.

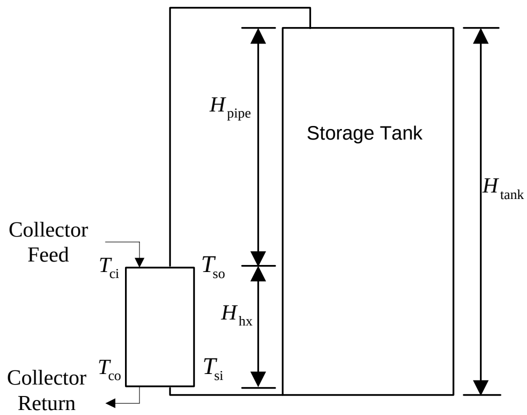


Fig. 4. Illustration of a NCHE heat exchanger showing location of reference temperatures.

It has been shown (Lin et al., 2000) that a NCHE unit can be characterized by two simple relationships: the pressure head versus the thermosyphon flow rate and the modified effectiveness versus the modified capacity ratio, i.e.,

$$\dot{m}_s = a * (\Delta P)^b \quad (3)$$

$$\varepsilon = c * C_{r_{\text{mod}}}{}^2 + d * C_{r_{\text{mod}}} \quad (4)$$

where $\dot{m}_S$ is the thermosyphon or natural convection flow rate. The constants, *a*, *b*, *c* and *d* can be derived by regression analysis performed on experimental test results obtained during simple charge tests. The values of the coefficients will be specific to a particular NCHE and side-arm thermosyphon loop configuration.

EXPERIMENTAL ANALYSIS

Individual tests were conducted to evaluate the performance of the NCHE considered in this study at a range of temperatures and charge-loop flowrates. In addition, tests were conducted on the multi-tank storage rig in both series and parallel configurations to determine the level of stratification, the heat transfer rates and total energy transferred.

Evaluation of Natural Convection Heat Exchangers

To determine the performance characteristics of the NCHE heat exchanger evaluated in this study, testing was conducted at a range of operating conditions. The results, Figs. 5 and 6, show the performance of a single heat exchanger under a variety of storage tank charge conditions and collector-loop flowrates and temperatures (Cruickshank et al, 2006c).

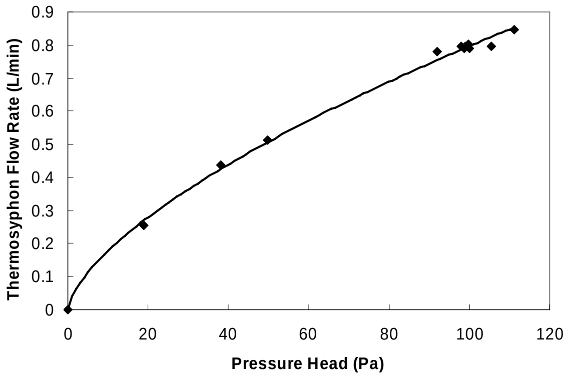


Fig. 5. Plot of experimental results showing the dependence of the thermosyphon flow rate on the pressure head (Cruickshank et al, 2006c).

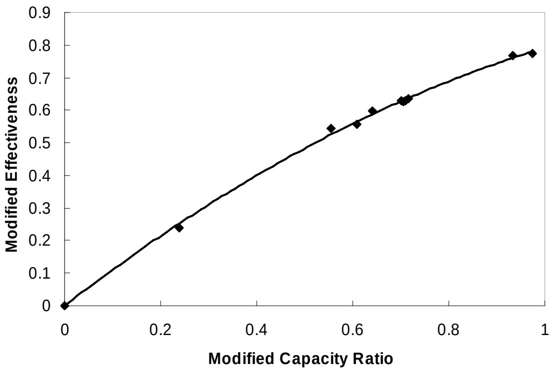


Fig. 6. Experimentally derived modified effectiveness as a function of modified capacity ratio (Cruickshank et al, 2006c).

Multi-tank Storage Evaluation

To evaluate the performance of the multi-tank storages, an experimental rig was constructed and instrumented at Queen's University (Cruickshank et al., 2006b). It consisted of three parts: a supply tank and heater (to simulate the solar collector array), a charge flow loop, and the storage unit under evaluation. The temperature of the charge loop was maintained at a constant set-point by a PID controller that adjusted the heat input. A positive-displacement pump was used to deliver hot fluid (a 50/50% by volume propylene glycol/water mixture) to each heat exchanger.

During the charge and discharge test sequences, a computer based data acquisition system was used to record flows and temperatures on the apparatus including the vertical temperature profiles in the storage tanks at 0.15 m intervals.

Series Connected. Data was recorded at a range of collector-loop flowrates and temperatures, for both series and parallel configurations (Cruickshank et al., 2006a).

Typical results for a charge sequence are shown below (Figs. 7 and 8) for a supply temperature of 50°C and the collector-loop flowrate of 1.5 L/min. (0.024 kg/s). The rate of heat transfer measured across each of the heat exchangers is shown in Fig. 8, and illustrates the sequential charging of the storage unit, i.e., tank 1 initially charges, followed by tanks 2 and 3.

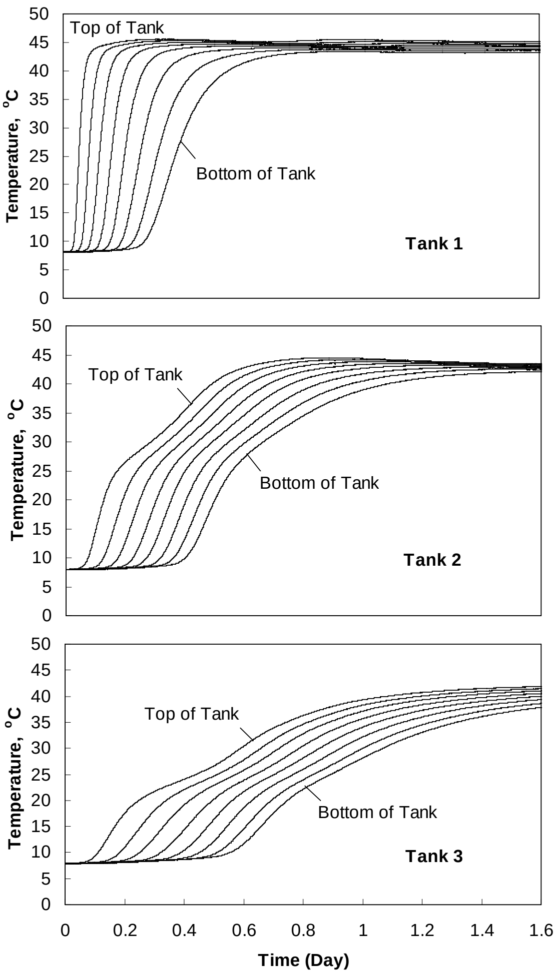


Fig. 7. Measured temperature profile of the series connected storage tanks during charging.

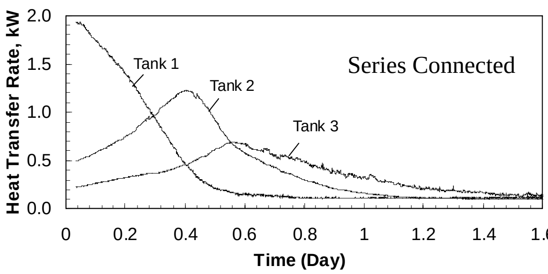


Fig. 8. Individual charge rates across each heat exchanger for the series configuration.

Parallel connected. Results measured for the same charge conditions, as shown for the series connected unit, are shown in Fig. 9, for the parallel configuration. The results indicate that all three tanks charged at identical rates and behaved very much like a single tank.

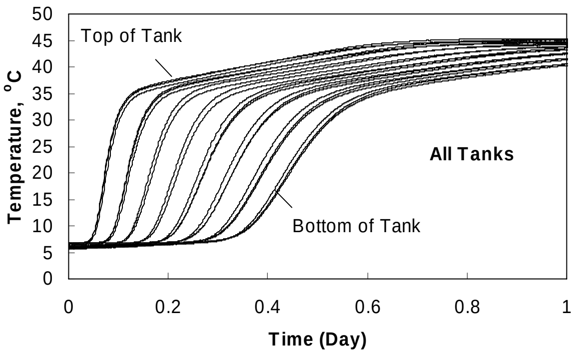


Fig. 9. Measured temperature profile of the parallel connected storage tanks during charging.

COMPUTER MODELING

The experimental test sequences were modeled with the TRNSYS program and the results compared for both the series and parallel cases. This computer model was then used to predict the operation of a series configured multi-tank storage in a typical multi-family application.

Modeling of multi-tank systems

To model the operation of the multi-tank systems, TRNSYS, Version 15, (TRNSYS, 2000), a transient simulation package, was used. This program provides many built-in modules describing mathematical and thermo-physical property functions.

TRNSYS TYPE 4, 38 and 60 routines model the operation of fixed volume, stratified storage tanks, however the TYPE 60 routine was found to best reproduce the experimentally measured temperature profiles in the storage tanks (Cruickshank et al, 2006d). For the simulations, it was assumed that each storage consisted of 30 equal-volume layers.

To model the operation of the side-arm NCHE units on each tank, custom TRNSYS modules were created to solve equations (3) and (4) and to determine the values of the natural convection flowrate and heat exchanger modified effectiveness. These values were calculated at each time-step of the simulation based on the hot-side charge temperature and the temperature distribution (i.e., the state of charge) of the storage tank. The coefficients of equations (3) and (4) were inputs to the custom TRNSYS modules and were determined based on non-linear regression curves that were fitted (by the method of least squares) to the experimental data shown in Figs. 5 and 6 (Cruickshank et al, 2006c).

The corresponding curve fits obtained were:

$$\dot{m}_s = 0.0398 * \Delta P^{0.6505}$$

$$\varepsilon_{\mathrm{mod}} = -0.3488 * C_{r_{\mathrm{mod}}}^2 + 1.1402 * C_{r_{\mathrm{mod}}}$$

To allow for a comparison with the experimental results, constant temperature charge sequences were modeled over a 40 hour period. A simulation time-step of 0.05 hours was used for the simulation.

Comparison of charge rates for the series and parallel configurations

To evaluate the accuracy of the storage model, the rates of charge and total energy delivered to the storage versus time are plotted in Figs. 10 and 11, respectively, for the series and parallel connected configurations. Both measured and simulated data are shown and are seen to correspond well.

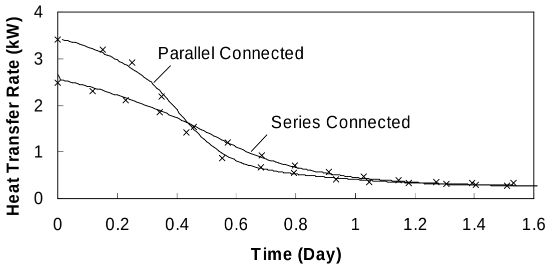


Fig. 10. Charge rate across all heat exchangers.

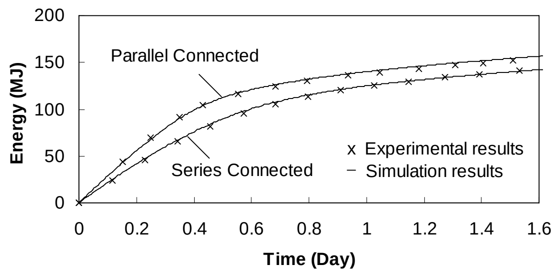


Fig. 11. Total energy delivered to the storage.

These results also show that, for the constant temperature charge case evaluated, the parallel configuration initially stored more energy than the series configuration. Over the 1.6 day charge period, the parallel configuration stored 10.1% more energy than the series configuration.

This difference, however, may be reduced when other charge scenarios are considered, e.g., variable supply temperatures and draw schedules. These latter effects occur in normal operations.

SIMULATION OF MULTI-FAMILY APPLICATION

To evaluate the performance of a multi-tank thermal storage, a typical multi-family, domestic hot water application was modeled using a TRNSYS model of the complete solar system including solar collectors, controller and storage unit. The system modeled was a series-connected multi-tank system consisting of three 270 L tanks, similar to the unit tested. Simulations were conducted for Montreal assuming the mains water temperature varied from 1.5 to 21°C over the course of a year, Table 2, and a load set-point temperature of 50°C.

Table 2.
Estimated monthly mains temperatures for Montreal.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Temp °C	3	2	2	1.5	5.5	12.5	18	21	20.5	18	11.5	6.5

Monthly average mains water temperatures were estimated from data provided by Bernier (Bernier, 2006). For comparison, a typical, small, single-tank unit (collector area 5.8 m^2, storage volume 270 L) and a large, single tank unit (collector area 17.15 m^2 and storage volume 810 L) were also modeled. A daily hot water draw profile consistent with the CSA standard-day recommendations (CAN/CSA-F379.1-88, 2004) for a 300 L/day draw was assumed in all cases. For both the large multi-tank and large single tank systems, the daily draw volume and collector area were increased to 3 times that of the small SDHW system, i.e., draw volume was 900 L/day and the collector area was 17.5 m^2. Similarly, for comparison, the collector loop flow rates increased to 3 times that of the small SDHW, in order to maintain a similar collector array efficiency and temperature distribution through the collectors. The full system computer models were then used to predict the operation of the three cases considered. The specifications of the three configurations compared are given in Table 3.

Table 3.
Simulation parameters for the 3 systems studied.

	Small Single Tank	Large Single Tank	Series Multi-Tank
Storage Volume	270 L	810 L	3 tanks x 270 L
Area of Collector, A_c	5.716 m^2	17.148 m^2	17.148 m^2
"*a*" Value in Eq. (3).	0.0398	0.0754	0.0398
Collector Flowrate, $\dot{m}_c$	74.16 kg/hr (1.2 L/min)	222.48 kg/hr (3.6 L/min)	222.48 kg/hr (3.6 L/min)
Heat Loss Coefficient, *U*	$5\frac{kJ}{hr\,m^2\,{}^oC}$	$5\frac{kJ}{hr\,m^2\,{}^oC}$	$5\frac{kJ}{hr\,m^2\,{}^oC}$
Load Volume	300 L	900 L	900 L

To compensate for the required increase in heat exchanger size for the large single tank, a comparison was done on both large systems (large single tank and multi-tank) with a zero heat loss condition. The pressure drop and effectiveness of the large single tank NCHE were normalized to provide a similar solar fraction as in the series multi-tank case. This was accomplished by modifying the "*a*" coefficient in Equation 3. Once a suitable "*a*" value was obtained, the system simulation was run with the normal heat loss condition. The results are shown in Table 4.

Table 4.
Annual simulation results for the 3 systems studied.

	Small Single Tank	Large Single Tank	Series Multi-Tank
Collected Solar Energy	11.04 GJ	29.33 GJ	31.60 GJ
Solar Energy Delivered to Load	10.56 GJ	29.30 GJ	29.15 GJ
No Solar Load	18.29 GJ	54.86 GJ	54.86 GJ
Storage Losses	0.038 GJ	-0.613 GJ	0.861 GJ
Parasitic Energy*	0.387 GJ	0.377 GJ	0.392 GJ
Solar Fraction	0.556	0.527	0.524
System Efficiency**	0.353	0.312	0.337

* Energy consumption for controller and circulation pump.

** $\varepsilon = \frac{Solar\ Energy\ Delivered\ to\ Load - Parasitic\ Energy}{Incident\ Solar\ Radiation\ per\ m^2 * Area\ of\ Collector}$

Figure 12 illiustrates the monthly solar energy delivered to the load for the three systems.

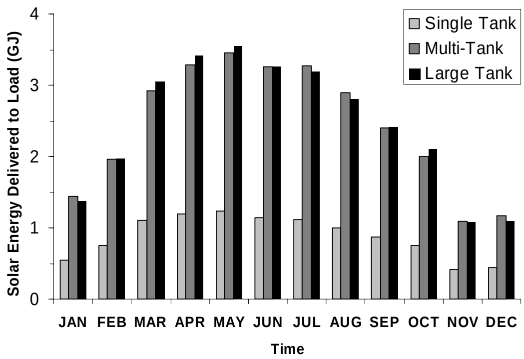


Fig. 12. Solar energy delivered to the load.

Discussion of Simulation Results

In the process of completing this comparison, it became apparent that the solar fraction, i.e.,

$$F_S = \frac{Solar\ Energy\ Delivered\ to\ Load - Parasitic\ Energy}{No\ Solar\ Load} \quad (5)$$

and the storage heat losses were dependant on the mains water temperature and the air temperature adjacent to the storage. Results showed that during the winter period, the cold portions of the storage tanks were heated from the surrounding air (assuming a 20°C environment adjacent to the storages). During the summer period, this situation is reversed and heat is lost from the storages to the surroundings. This makes the selection of the optimum insulation level for these thermal storages a fairly complex issue that depends on the storage volume to surface area ratio, and the mains and room air temperature, etc. As well, if the positive gains to the thermal storages, during the winter period, add to the building space-heating load, there may be little benefit to the building owner.

For the cases studied, the insulation level in the storage tanks was assumed to be equal (U = 5 kJ/m^2 ^{o}C) which resulted in an annual net heat loss from the storage of 0.861 GJ for the series multi-tank system. At a similar insulation level, the large single storage showed a slightly negative net annual heat loss (i.e., corresponding to a net heat gain).

In both cases, the heat losses or gains from the surroundings to the storage units were less than 2% of the annual load energy requirement. It is also worth noting (Table 4) that the solar fractions and system efficiencies of both the large single tank and the series, multi-tank systems are very close.

CONCLUSIONS

The performance of a medium sized, multi-tank thermal storage was investigated by experiment and computer simulation. Both simulation and measured test results show that high degrees of stratification can occur in both series and parallel multi-tank storages. In the case of the series connected tanks, the results also indicate the feasibility of using side-arm, natural convection heat exchangers in a multi-tank storage system. This arrangement has the advantage of allowing the use of low cost, conventional hot water storage tanks.

Under a constant temperature charge scenerio, the experimental and simulation results indicate that slightly higher storage rates were achieved with the parallel storage configuration relative to the series case. However, considerable difficulty was experienced to achieve a balanced flow distribution in the parallel configuration. Consequently, system designers may choose to utilize the series configuration.

Simulation results for the modelling of a multi-family solar domestic hot water system using the series-connected, multi-tank storage indicate that the annual performance is comparable to a system incorporating a single storage of equal volume. For the same insulation levels and similar heat exchanger capacities, solar fractions of 52.7 and 52.4 % were obtained, respectively, for the large single-tank and multi-tank configurations.

ACKNOWLEDGEMENTS

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