Experimental and Simulated Performance of Commercially available Solar and Heat-pump Water Heaters in New Zealand

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New Zealand is currently trying to increase the penetration of solar hot water heaters in domestic applications. As part of a NZ government study to investigate energy efficiency in domestic housing we have been testing a selection of energy efficient hot water systems. The systems include a heat-pump system, a flat plate thermosyphon system, a flat plate pumped circulation system and an evacuated tube system. The systems have been monitored for performance in Dunedin for a 12 month period. A programmable data logging system has been established for the duration of this period to log temperature, flow rate and weather data. All systems are permanently connected to the electricity supply to supply boost heating. Performance of the four systems is calculated daily and represented by a COP value (Co-efficient of Performance).

The volume of water extracted from each of the four systems represents approximately half of their respective storage tank volumes and is scheduled to be roughly consistent with actual hot water use in a separate study investigating energy use in public housing in NZ. Performance of some of the systems has been disappointing and is strongly dependant on the time of draw off of the hot water.

A computer simulation package, TRNSYS™, has been used to model the performance of the same systems. Weather data collected from the site has been entered into the model and overall performance values obtained. These values have then been compared to those obtained through the physical experiment to determine the accuracy of the model. These models will give confidence for estimating the performance of the same systems for other New Zealand locations.

1. INTRODUCTION

As the long term supply of fossil fuels becomes more problematic for both NZ and the world, options for alternative energy sources become increasingly urgent; solar hot water systems are one option that could alleviate the energy supply problem. At the end of 2004, it was estimated some 25,200 solar water heaters were installed on New Zealand homes (EHMS, 2005) - equivalent to 0.63 systems per 100 people. The energy received by a horizontal surface in New Zealand ranges from around 2.5 to 4.5 kWh/m^2/day (EECA/CAE, 1996). In comparison, Germany has similar insolation and climatic conditions to New Zealand and yet the penetration of solar water heating there is much higher, at approximately 8.75 systems per 100 people (Weiss et al., 2005). A large opportunity therefore exists to increase penetration of solar hot water systems within the New Zealand residential sector.

Both the present Labour Government and the Green Party in NZ have a strong policy in this regards. According to the recent (2005) election policy of the Greens, they are proposing an ambitious scheme to have half a million square meters of solar collectors installed in New Zealand within five years. Their scheme relies on reducing costs by large scale deployment of a limited number of system types. There is thus some incentive to make sure operating characteristics of available systems exist so that the best choice can be made for deployment. In addition, the government housing program, Housing NZ, is concentrating on improving energy efficiency in general in the residential sector.

As part of a Foundation for Research in Science and Technology (FRST) grant, a selection of energy efficient hot water systems have been tested at Otago University. The systems tested in this research project include a flat plate glycol-circuit thermosyphon system with a mantle heat exchanger surrounding the horizontal tank, a flat plate pumped circulation system retro-fitted to an existing vertical domestic hot water cylinder, an evacuated tube system with a working fluid in the tubes and horizontal tank, and a heat pump system with a wrap-around condenser.

2. BACKGROUND

The overall performance of a solar or heat pump system that is permanently connected to a (main or backup) electricity supply can be represented by the Coefficient of Performance (COP), and is defined as the ratio of the thermal energy (referenced to the actual input water temperature) drawn off from the system (Q_{load}) to the electrical energy (Q_{elec}) input to the system. This is expressed by Equation 1.

$$COP = Q_{out} / Q_{elec} \tag{1}$$

A COP of greater than one will result if more energy is extracted from the system than the electrical energy input, as should be the case with solar and heat pump water heaters. By the way of comparison, a typical New Zealand standard domestic hot water cylinder (electric resistance heating) has a COP equivalent of 0.66 (BRANZ, 2004), which means that the standing losses are around 34%.

Factors which affect the performance of SDHW systems are well agreed and have been the subject of investigation for many decades (Hendtlass (1983), Jordan and Vajen (2000), Michaelides and Wilson (1995), Morrison (2001)). The factors include local climatic patterns, collector inclination and orientation, load patterns, system configuration, and installation.

As the sun cannot be turned on or off the temperature of the stored water in solar assisted systems can often be above the set-point temperature which is controlled by the thermostat switching the electrical back up supply on and off. This means that a set volume of water drawn off from a solar system may have a varying Q_{out} on any given day. In the present data collection, constant energy content of the water removed to supply the load (referenced to water at zero degrees C) was used. This was achieved by enabling a data logger to measure the input and output water temperatures and flow rates to stop the hot water removal when a set quantity of hot water had been released. The specified cut-off point for Q_{load} was calculated to be equivalent to the energy content of half the volume of the tank, for a difference between the set-point temperature of the tank (60 ^{o}C) and a reference temperature (T_{ref}) of 0 °C.

$$Q_{load}(kJ) = \dot{m} C_p (T_{out} - T_{ref}) \tag{2}$$

The research tested the performance of the systems as 'whole' products, including installation, which was performed by local suppliers of the products under their own specifications, with no influence from the University. Although the tests were designed to represent as close to a domestic situation as possible, this was limited by the load pattern of water draw off from each system. The data logger was programmed to release water from each system daily at either 8am, 6pm, or a combination of both. These times were chosen to represent typical load distribution patterns in New Zealand homes (Hendtlass (1983), Shen (2004)). The majority of daily draw offs were programmed for 8am, to reflect the morning consumption peak being larger than that of the evening.

3. METHODOLOGY

Flow sensors and solenoid valves were connected to the hot water outlet pipes of all four units. Thermocouples, used to measure water temperatures, were fixed to the respective copper pipes and wrapped tightly with closed-cell insulation foam. These sensors were then connected to a 28 channel data logger (DataTaker) with internal memory. A program was written using software designed for the data logger which controlled all the tasks and actions, including when and how much water to release from each system, and logging temperature, flow rate, electrical consumption and weather data. Data was then downloaded from the logger and used to calculate average monthly and annual COP values for each of the four systems. A sub-test was conducted to find the overall heat loss coefficient of each of the systems in watts of electrical energy input required to maintain the tank set point temperature, per degree Kelvin temperature difference with the surrounding air. These tests were performed overnight to prevent any solar gain.

Calibration of key instrumentation was undertaken before, during and after the experimental data collection. Thermocouples were calibrated using an independently calibrated platinum resistance thermometer, flow meters using a data logging sub-routine for water draw off from the systems into a container and measuring the mass with precision scales, and pyranometers using a calibrated reference pyranometer with a valid calibration certificate.

One of the systems (flat plate thermosyphon) was modeled using TRNSYS software. Version 16 of TRNSYS is used in this project. A ten second time step was used for the simulation. The key components in the model are described below. No weather data file for the Dunedin location was available in a format recognisable by TRNSYS, so this file was constructed using data downloaded from the University of Otago Physics Department weather station, located adjacent to the experimental set-up. The data logging period used for all analysis and the data file was the period 1 September 2004 to 31 August 2005. The data was processed in the TRNSYS model using the component *Type109-User*.

TRNSYS component *Type45a* was used to model the flat plate thermosyphon collector with integral storage. A list of 39 parameters defined this component. Whenever possible, parameters were found by direct measurement of the system or from manufacture specifications. Collector performance results of the same system performed by the Solar Rating and Certification Corporation, Florida (SRCC, 2004) were used to define parameters for Efficiency slope, Tested flow rate and the Incidence angle modifier constant. A limitation exists in the *Type45a* component, however, as this component did not incorporate a glycol circuit and mantle heat exchanger as present on the tested system. Component *Type14b* was used to supply water in the model at either 8am or 6pm as according to the experimental testing schedule. A constant energy routine was also developed for the model, whereby an integrator component was used to calculate the accumulated amount of energy leaving the *Type45a* component. This value was sent to a *Type2d* controller which stopped the flow of feed-water entering the *Type45a* component when the specified energy value was reached.

4. RESULTS

Figures 1 to 4 show the COP for each system on a monthly basis for Dunedin. The dashed horizontal line on each plot represents the annual average COP. Respective tilted radiation levels are included on the figures for the three solar systems, and ambient temperature for the heat pump system.

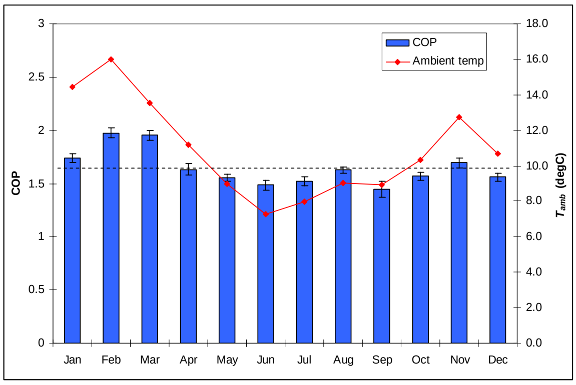

Figure 1: Evacuated tube – COP and G_T

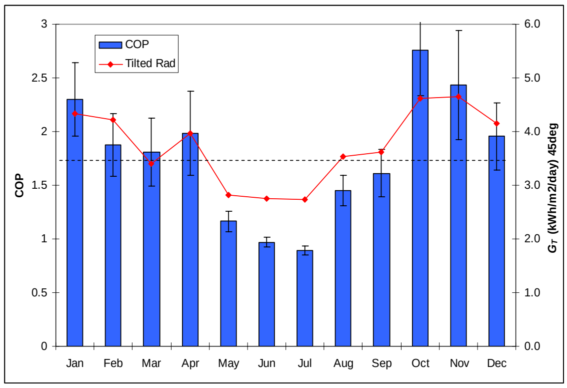

Figure 2: Heat pump system - COP and T_{amb}

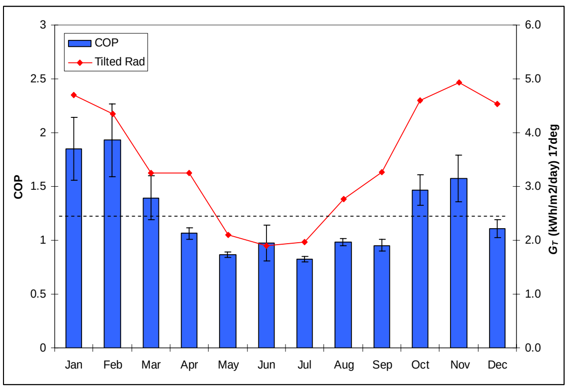

Figure 3: Flat-plate thermosyphon - COP and G_T

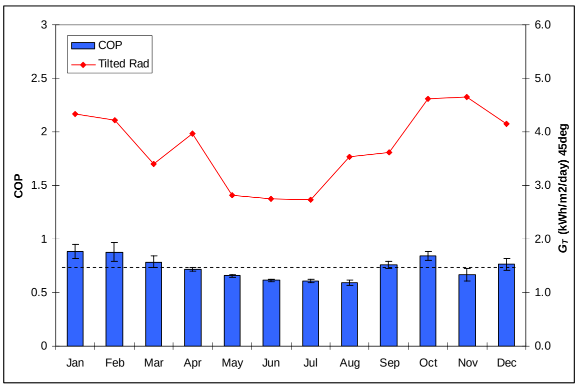

Figure 4: Flat-plate pumped - COP and G_T

The annual COP of the four systems for Dunedin for the test period September 1st 2004 to August 31st 2005 is given in Table 1, alongside the overall tank heat loss coefficient for each of the four systems in watts of electrical input required per degree Kelvin. Economic analysis of the four systems is included in the table based on the following assumptions: the volume of water drawn from each system per day was equivalent to half the tank volume (at a temperature set-point 60 ^{o}C with an average input water temperature of 12.4 ^{o}C). Note the actual set point for the heat pump system was 55 ^{o}C. The average cost of electricity in Dunedin at the time of calculation was $0.186/kWh which includes the daily fixed price charge spread over the average household electricity consumption (7.8 MWh/year), and with a system life cycle of 20 years.

To see how the systems would perform in warmer areas of New Zealand, the performance of the systems were estimated for Auckland, New Zealand. This was achieved by observing the fortuitous circumstance that for the month of February both the monthly average ambient temperature (16.0°C as measured) and the monthly average insolation (4.21 kWh/m^2/day as measured) for Dunedin was very close to the average annual temperature (15.1°C) and the average annual insolation (4.17 kWh/m^2/day) for Auckland. The climate parameters for Auckland were 20 year averages obtained from NIWA. The average monthly COP values for February for Dunedin were then estimated to be annual averages for Auckland. This estimation of course would not account for the annual variation that would occur in Auckland but, as is well known, the weather is Dunedin is highly variable and so the extrapolation was thought to be a reasonable one. These final data are given in Table 1.

Table 1: Thermal and economic performance of tested systems, New Zealand

DUNEDIN	**Evacuated tube**	**Heat pump**	**Flat-plate thermosyphon**	**Flat-plate pumped**
COP	**1.73 ± 0.09**	**1.64 ± 0.02**	**1.22 ± 0.05**	**0.73 ± 0.01**
Tank heat loss co-eff (W/K)	1.08	1.53	1.17	0.64
Capital ($ incl. installation)	$2,570	$5,420	$5,980	$4,800
Elec. Savings ($/yr)	$281	$510	$392	$44
NPV (20yr life cycle / 5% discount rate)	$936	$263	-$1,102	-$4,257
IRR (%)	9.0%	5.6%	2.7%	-12.6%
AUCKLAND (estimated)				
COP	1.88	1.97	1.93	0.88
Capital ($ incl. installation)	$2,470	$5,320	$5,880	$4,700
Elec. Savings ($/yr)	$295	$567	$561	$114
NPV (20yr life cycle / 5% discount rate)	$1,208	$1,005	$1,113	-$3,283
IRR (%)	10.3%	7.1%	7.1%	-6.1%

Results from the TRNSYS simulation are shown in Table 2. Run 3 represents the modeled result for annual COP as per the conditions of the experiment. Runs 4 and 5 investigate the effect of thermostat and heating element position on the overall performance of the system.

Table 2: Simulated results of flat-plate thermosyphon system using TRNSYS 16 for Dunedin

Run	Description	Annual COP
1	Flat-plate thermosyphon model - *8am load only*	1.50
2	Flat-plate thermosyphon model - *6pm load only*	1.31
3	Flat-plate thermosyphon model - *8am and 6pm loads as per experiment*	**1.45**
-	*(Experimental result)*	**1.22**
4	Heating element shifted down from 0.22m to 0.1m above tank bottom - *8am load*	1.21
5	Heating element = 0.1m / Thermostat shifted from 0.3m to 0.1m - *8am load*	1.17

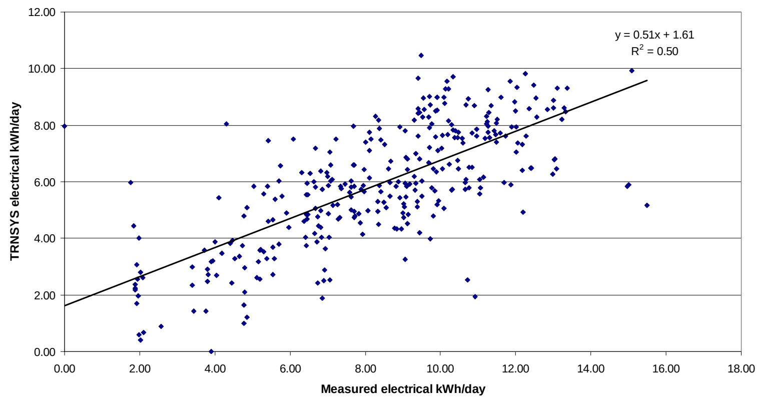

Figure 5: Measured vs. Simulated daily electrical energy consumption for flat-plate thermosyphon system

Figure 5 shows the correlation between daily measured and daily simulated electrical consumption (Q_{elec} in Equation 1) of the flat-plate thermosyphon system. If on a particular day during the experimental period water was drawn off from the system at 8am, then the data from the 8am simulation (Run 1) for that day would be used in the plot. The same holds true for 6pm and simulation Run 2.

5. DISCUSSION

The average annual climatic conditions in Dunedin for the period 1974 to 2000 show an average annual ambient temperature of 11.0°C and an average annual horizontal radiation of 3.17 kWh/m^2/day (NIWA, 2005). During the test-year the average ambient temperature was 10.9°C and average horizontal radiation 3.09 kWh/m^2/day. It is therefore considered that the present results would be representative of average Dunedin conditions.

The evacuated tube system yielded the highest overall COP for the Dunedin location of 1.73 ± 0.09, followed by the heat pump system and the flat-plate thermosyphon, respectively. The flat-plate pumped flow system gave a far lower COP of 0.73 ± 0.01, which was not much better than a standard resistive electric hot water cylinder, with a typical COP of 0.66 (NZ average). The cause of this low result is most likely due to the retrofit installation of the system to a standard domestic hot water cylinder. The vertical cylinder, like most standard domestic systems, has an electric heating element and thermostat located close to the bottom of the tank. Cold replacement water enters the bottom of the tank when hot water is drawn from the top to supply the load. If the thermostat is located near the bottom of the tank, the electric heating element will turn on soon after any water is drawn from the system. In addition there were several other physical problems with this system including, a defective absorber surface which had to be replaced (before September 2004), leaking valves and incorrect system plumbing (rectified 11 August 2005). The manufacturers of this pumped system noted the results and acknowledged the possible reasons for this. They also pointed out that our results contradicted earlier tests performed by the Consumers Institute in 2001 (Consumer 2001). These tests found that the same panel used out-performed two flat-plate thermosyphon panels. The Consumer tests, however, did not measure the whole system COP and may have overlooked the problem with regard to the heat exchange in the storage tank. The effect of the retrofit to a cylinder with a low positioned thermostat is supported by the simulation results shown in Table 2 for the flat-plate thermosyphon system, which found lowering the thermostat and/or the heating element in the tank lowered the system COP.

In general it is accepted that in higher latitude locations, the performance of evacuated tube collectors with integral storage tanks is better than that of typical flat-plate collectors (Budihardjo et al. (2002), Morrison (2001)). This is verified by the results for Dunedin, latitude -45.87°, shown in Table 1. In comparison, the highest performing solar hot water system in Auckland, latitude -36.92°, is the flat-plate thermosyphon system with an estimated COP of 1.93. However the heat pump system in fact gives a slightly better performance for Auckland, with an estimated COP of 1.97.

Although the value of COP effectively determines the overall performance of the tested systems and allows comparisons to be made, it is of more use to potential buyers of solar and heat pump systems to compare financial figures which incorporate both performance and the costs of the systems. For Dunedin the evacuated tube system gives an attractive Internal Rate of Return (IRR) of 9.0% and a positive Net Present Value (NPV) of $936 using a discount rate of 5% (after tax). The heat pump system in Dunedin also gives a positive NPV of $263, while both flat-plate models give negative NPV's. For the Auckland estimation the evacuated tube system still yields the most favourable economic result with an IRR of 10.3% due to its low capital cost, despite having a slightly lower COP than both the heat pump or flat-plate thermosyphon systems. In the Auckland location all systems except the flat-plate pumped circulation system give attractive economic results.

The annual COP derived from the TRNSYS model for the flat-plate thermosyphon model was 19% higher than that measured for the test year. The reason for this difference is due to either a lower level of thermal stratification in the actual system than the model allowed for (runs 1 -3) or the lack of the mantle heat exchanger being incorporated into the model. That the former is a reasonable assumption can be seen from the simulation results, for the condition when the position of the heating element (and or sensor) is lowered (runs 4 and 5), showing simulation results which agree closely with the experimental results. The large scatter of the daily comparisons between simulation and experiment (Figure 5) show how variable the performance of the actual system is on a daily basis.

It is also important to note that the results obtained are for solar systems permanently connected to a backup electricity supply and that if the back up is removed, or controlled intelligently, considerable improvement in COP will result (the COP for a stand-alone solar system is of course infinitely large in that it uses no electrical input).

6. CONCLUSION

The main conclusion from this study is that it is important to test actual systems before making any assumptions about energy savings and or economic performance. In particular it can be seen that the high cost of installed systems in NZ makes it difficult for them to achieve good economic return on capital. It is also clear that evacuated tube systems need to be taken into serious consideration as a preferred system type, especially for the cooler parts of the country. The performance of the flat-plate pumped circulation system has proved to be highly suspect and possibly dependant on the fact that it was a 'retrofit' installation to an existing domestic hot water cylinder. This is an important finding, as there are no on site performance tests for solar hot water systems undertaken and many New Zealand systems may be seriously underperforming, perhaps unbeknown to the house owner.

Further work needs to be done to quantify the behavior of the systems for different climatic regions in NZ. This will need to include modifications to the TRNSYS model to incorporate the mantle heat exchanger and glycol circuit for the flat plate thermosyphon system and modeling of the other systems.

7. REFERENCES

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