Solar Energy Vol. 33, No. 1, pp. 83–87, 1984
Printed in the U.S.A.

0038-092X/84 \$3.00 + .00
Pergamon Press Ltd.

TECHNICAL NOTE

Variable volume storage and stratified storage for improved water heater performance

L. F. JESCH
Solar Energy Laboratory, Department of Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, England

and

J. E. BRAUN
Solar Energy Laboratory, University of Wisconsin-Madison, 1500 Johnson Drive, Madison, WI 53706, U.S.A.

(*Received* 14 *December* 1982; *accepted* 12 *August* 1983)

1. INTRODUCTION

Conventional solar water heating systems use fixed storage volumes and high circulation rates through collector loops, with resulting high values of the collector overall efficiency factor, F_R. In contrast, it is possible to use low and variable flow rates and variable volume storage[1–3] to achieve significantly improved system performance. This note describes how these systems might be operated and describes simulations studies that indicate the kind of improvements to be expected. For comparison purposes, simulation results are presented for variable volume systems with fixed and variable flow rates along with results for fixed volume, fixed flow rate systems.

2. SYSTEM DESCRIPTIONS AND MODELING

A conventional recirculating solar water heater with fixed volume storage is shown schematically in Fig. 1. Water is drawn from the system at the desired temperature and replaced with make-up water at the mains temperature. A separate auxiliary boosts the temperature of the solar preheated water if necessary, while a tempering valve limits the temperature of the delivered water to the set temperature. Due to the difference in the time distribution of the load and the incident solar, the storage temperature rises during high solar radiation periods reducing the collector efficiency. Stratified storage tanks provide some improvement by recirculating water from the coldest part of storage.

An alternative means of reducing the collector inlet temperature is to use a variable volume storage system as illustrated in Fig. 2. In its simplest form, the system does not recirculate and the inlet temperature to the collector is the mains temperature. Since the level of the tank is allowed to vary, the collector flow at any instant need not equal the load flow. However, if the total collector flow over a day (or longer) is greater than the load flow, then the tank may fill and it may be advantageous to allow recirculation. In this study, recirculation is allowed when the tank is full. If, however, the tank is empty, then make-up water is added directly to the auxiliary tank to satisfy the demand. As in the conventional system, tempering is provided to avoid delivering overheated water.

If variable storage volumes of water are to be used, then the optimal collector flow rates used will be different than those used in conventional systems. To avoid recirculation, the total collector flow over a day must be on the order of the load flow. As a result, the instantaneous collector flows will be much lower than those encountered in conventional DHW systems. In order to make valid comparisons between the performance of systems with low and high flow rates, it is important to properly model the effect of flow rate on performance. In this study, the computer program TRNSYS[4] was used to simulate the performance of both the fixed and variable volume systems. Where necessary, new component models were created. A brief description of the model formulations follows.

The thermal performance of a flat-plate collector can be modeled according to the Hottel–Whillier equation as

$$Q_u = A_c(F_R(\tau\alpha)G_T - F_R U_L(T_i - T_a)). \quad (1)$$

The flow rate affects both the parameters $F_R(\tau\alpha)$ and $F_R U_L$ through changes in F_R. Most collector manufacturers publish values of these collector parameters at a particular test flow rate. An analytical correction to values of $F_R(\tau\alpha)$ and $F_R U_L$ for flow rates other than that of the test can be obtained as outlined in Ref. [5]. The ratio, r, by which $F_R(\tau\alpha)$ and $F_R U_L$ are corrected is given here as

$$r = \frac{\left[\dfrac{\dot{m}_c C_p}{A_c F' U_L}\left(1 - e^{-A_c F U_L/\dot{m}_c C_p}\right)\right]_{\text{use}}}{\left[\dfrac{\dot{m}_c C_p}{A_c F' U_L}\left(1 - e^{-A_c F U_L/(\dot{m}_c C_p)}\right)\right]_{\text{test}}} \quad (2)$$

where the subscripts use and test imply whether the flow rates correspond to those for actual or test conditions.

In order to use this equation, it is necessary to estimate $F'U_L$. For test conditions,

$$F'U_L = \left[\frac{\dot{m}_c C_p}{A_c}\ln\left(1 - \frac{A_c F_R U_L}{\dot{m}_c C_p}\right)\right]_{\text{test}}. \quad (3)$$

Both the overall loss coefficient, U_L and the fin efficiency factor, F', change as the heat transfer coefficient between the working fluid and the tube or duct change. For typical liquid collector designs with conventional flow rates, the flow is generally laminar and the heat transfer coefficient (also F' and U_L) is insensitive to changes in flow rate. Therefore, by using the value of $F'U_L$ derived from test conditions in both the numerator and denominator of eqn (2), a good estimate of $F_R(\tau\alpha)$ and $F_R U_L$ at any flow rate can be obtained.

The fixed volume storage tank is modeled by assuming the tank consists of N fully-mixed equal size segments[4]. The degree of stratification is determined by the value of N. The fluid entering the tank is assumed to go to the segment to which it is closest in temperature. With sufficient segments, this permits a maximum degree of stratification. If N is 1, the storage is fully-mixed and no stratification is possible.

The variable volume tank is modeled as a single-node fully-mixed tank with variable mass of water. The two differential equations describing the rate of change of mass

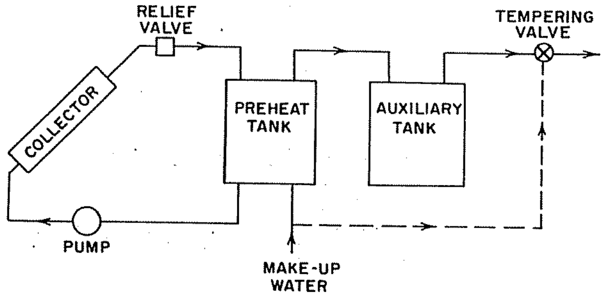

Fig. 1. Schematic of a conventional recirculating solar water heater.

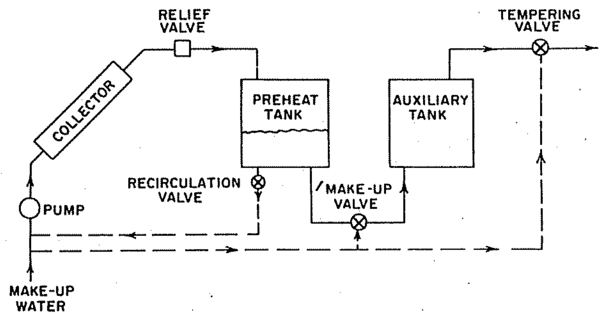

Fig. 2. Schematic of a variable volume storage solar water heater.

and internal energy are given as

$$MC_v\frac{dT}{dt} = \dot{m}_c C_p T_0 - \dot{m}_L C_p T - \dot{m}_r C_p T - (UA)_t(T - T_{env}) \quad (4)$$

$$\frac{dM}{dt} = \dot{m}_c - \dot{m}_L - \dot{m}_r. \quad (5)$$

These two simultaneous differential equations are solved analytically for each simulation timestep. If the tank is not full at the end of an interval, then the flow rate recirculated to the collectors, $\dot{m}_r$, is zero. If, however, the difference between the collector and load flows is large enough so that the volume of the water at the end of a timestep would exceed the volume of the tank, then $\dot{m}_r$ is equal to the flow rate necessary for this condition not to occur.

Typically, collector pumps are controlled with thermostats that use the temperature differential across the collectors as the criterion for operation. The temperature rise requirement is most appropriately chosen so that the energy collection at the point of turn-on exceeds the pumping power. Since pumping power is a non-linear function of flow rate, it is not reasonable to study the effect of flow rate on system performance, while maintaining a fixed differential requirement for operation. In this study, both the fixed and variable volume systems are controlled so that the collector operates only if the net useful collection is greater than the power required to operate the pumps. The power versus mass flow characteristics used in this study are a third order polynomial curve fit to measured data for several pumps at the Birmingham Solar Laboratory.

A daily load of 2600 kg of water delivered at 55°C was used. The distribution of the load was the same every day, having two peaks during the daylight hours and one at night. The water mains temperature varied sinusoidally during the year with a maximum of 15°C and minimum of 5°C. Table 1 gives the other system parameters employed in the simulations. Results for two collectors of different characteristics as defined in Table 1 will be presented. Collector A might be representative of an inexpensive collector, while collector *B* might be a more expensive type.

3. FIXED COLLECTOR FLOW

One of the simplest means of operating a collector pump is to have it turn on with a fixed flow rate whenever the

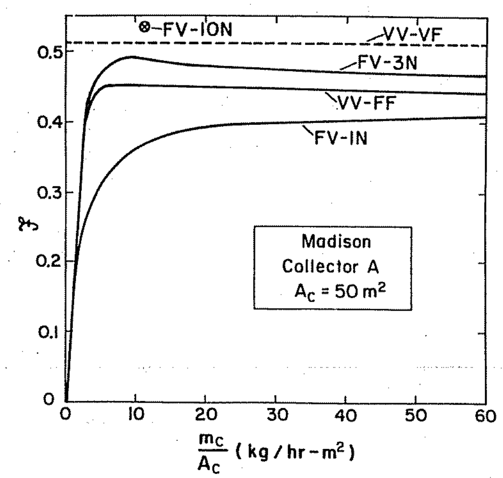

Fig. 3. Effect of flow rate on annual solar fraction for fixed and variable volume systems in Madison.

Table 1. System parameters

Description	Value
Collector A	
test flow rate	72 $kg/hr\text{-}m^2$
$F_R(\tau\alpha)\|test$	.62
$F_RU_L\|test$	6 $W/m^2\text{-}°C$
b_o	0.3
Collector B	
test flow rate	72 $kg/hr\text{-}m^2$
$F_R(\tau\alpha)\|test$	.715
$F_RU_L\|test$	3.8 $W/m^2\text{-}°C$
b_o	.17
Preheat Tank	
volume per unit collector area	75 $liters/m^2$
loss coefficient	.40 $W/m^2\text{-}°C$
Auxiliary Tank	
volume	1.5 m^3
loss coefficient	.40 $W/m^2\text{-}°C$

differential temperature across the collector exceeds a value necessary for the energy collection to exceed the pumping power. With a variable volume system, this strategy results in periods of recirculation between collector and storage. However, even with this simple strategy, significant improvement can be realized with a variable volume system.

Figure 3 presents a comparison for Madison of the effect of flow rate on annual performance for a variable volume system with fixed flow rate (VV–FF) and fixed volume systems with different degrees of stratification, fully-mixed (FV–1N) and 3 node (FV–3N). For the fixed volume system with a fully-mixed storage, the performance approaches the asymptotic value in the range of 50–60 kg/hr m². This is typical of flow rates used in practice. If tank stratification is considered, then the optimum flow rate is between 5 and 10 kg/hr m² or an order of magnitude less than conventional wisdom dictates. This is consistent with results of previous studies[6–8]. Tabor[9] also noted that at low flow rates, high stratification systems would perform about as well as high flow rate systems without stratification. At high flow rates, the tank destratifies reducing collector efficiency by raising the inlet temperatures. This effect is more than enough to offset reductions in efficiency due to lower values of F_R. Stratification is highly dependent upon the design of the tank. At conventional flow rates a 3 node tank model represents a good design that may not be obtained in general practice. Experimental studies[10, 11] have shown that a high degree of thermal stratification is difficult to maintain at high collector flow rates. In may cases, a fully-mixed storage model may be closest to reality. At low flow rates, however, it may be easier to obtain good stratification and a 3 node model may underestimate the actual degree of stratification. The solar fraction for a fixed volume system modeled with a 10 node tank operating at 10 kg/hr m² is marked with an ⊗ in Fig. 3. When compared with a fully-mixed tank operating at conventional flow rates, the 10 node representation shows a 30 per cent improvement in delivered energy. Experimental work needs not to be performed to evaluate the possibility of this kind of improvement.

The optimum performance for the variable volume system with fixed flow rate also occurs at low flow rates. Lower flow rates mean less recirculation between the collector and storage, resulting in lower inlet temperatures. Once again, this effect offsets reductions in F_R due to lower flow rates.

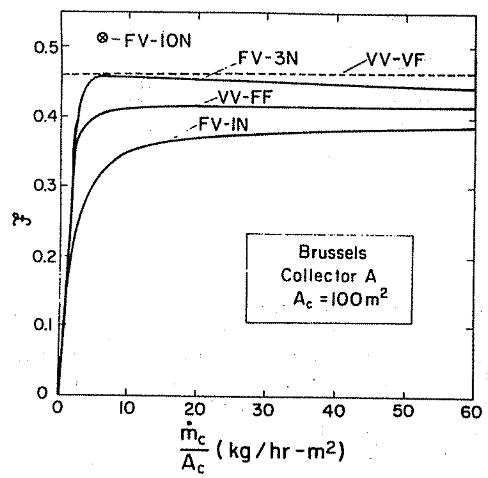

Fig. 4. Effect of flow rate on annual solar fraction for fixed and variable volume systems in Brussels.

If the VV–FF system operating at low flow rates is compared with the fully-mixed fixed volume system operating at conventional flow rates, then there is a 10 per cent improvement in the delivered energy. Also shown in Fig. 3 is a dashed line indicating the performance of a variable volume system with variable flow. This will be discussed in the next section. Similar results for fixed volume and variable volume systems were obtained for Brussels as illustrated in Fig. 4.

4. VARIABLE COLLECTOR FLOW

With variable volume storage and variable collector flow, intuition leads one to believe that a good control strategy is one that maximizes flow while limiting recirculation between the collector and storage. In order to accomplish this, the integrated flow rate over some period of time (depending on the size of storage) must equal the load flow or

$$\int \dot{m}_c \, dt = \int \dot{m}_L \, dt. \tag{6}$$

Table 2. Annual performance comparisons for Madison with collector A

System	$\mathcal{F}_{max}$
FV-IN	.41
FV-3N	.49
FV-10N	.53
VV-FF	.45
VV-VF	.51

Table 3. Annual performance comparisons for Brussels with collector A

System	$\mathcal{F}_{max}$
FV-IN	.39
FV-3N	.46
FV-10N	.51
VV-FF	.42
VV-VF	.46

Table 4. Annual performance comparisons for Madison with collector B

System	$\mathcal{F}_{max}$
FV-IN	.58
FV-3N	.65
FV-10N	.69
VV-FF	.62
VV-VF	.68

Within this constraint, there are a variety of control strategies. One possibility is to control the flow rate to maintain a fixed outlet temperature. This outlet temperature would have to vary with time of the year in order to meet the constraint of eqn (6). An expression for the flow rate necessary to achieve a particular outlet temperature, T_0, is given in terms of the meteorological conditions and collector parameters as

$$\dot{m}_c = \frac{-A_c F' U_L}{C_p \ln\left[1 - \dfrac{(T_0 - T_i)}{\dfrac{F_R(\tau\alpha)|_{test}}{F_R U_L|_{test}} G_T - (T_i - T_a)}\right]} \tag{7}$$

Through processing of hourly weather data, the outlet temperature that satisfies the cosntraint of eqn (6) over a specified period of time can be determined.

Another approach to controlling the collector flow rate is to make it proportional to the utilizable radiation or

$$\dot{m}_c = J(G_T - G_{TC})^+ \tag{8}$$

where the + sign indicates that only positive values are considered.

If the constraint of eqn (6) is applied then

$$J = \frac{\int \dot{m}_c \, dt}{\int (G_T - G_{TC})^+ \, dt}. \tag{9}$$

If the period of time is a month, then this is the monthly total usage divided by the utilizable energy or

$$J = \frac{M_L}{\bar{\phi} \bar{H}_T N} \tag{10}$$

where $\bar{H}_T$ can be determined as outlined by Klein[12]. Several procedures are available for evaluating $\bar{\phi}$ [13–18].

Useful energy collection was determined for the month of May in Madison for each of the two control strategies discussed above. Collector A was used with a mains temperature of 10°C. The fixed outlet temperature and proportionality constant J that satisfy eqn (6) for this month were found to be 40.5°C and 0.1217. Of the two methods tried, the radiation control proved to be the best. The solar energy collection with flow rate proportional to utilizable radiation was 220 MJ/m², while the collection for the fixed outlet control strategy was 207 MJ/m². Similar results were obtained for Brussels.

Comparisons of fixed and variable flow strategies for systems operating in Madison and Brussels are shown in Figs. 3 and 4 for collector A. The curves, as discussed in the previous section, show the effect of flow rate on system performance for the fixed flow rate systems. The performance of a variable volume system with variable flow (VV–VF) controlled by radiation is shown as a dashed horizontal line. The optimal numbers from these figures are summarized in Tables 2 and 3. The VV–VF system performs 25 per cent better than the fixed volume fully-mixed system operating at high flow rates and slightly worse than a fixed volume system modeled with a 10 node tank and operating at a low flow rate. Similar results are given in Table 4 for a system using collector B located in Madison.

5. CONCLUSIONS

Both variable volume and highly stratified fixed volume systems operating at low collector flow rates provide significant improvements in thermal performance over conventional systems. When the variable volume store is coupled with variable collector flow, further improvement is realized. For the particular system tested, the improvement in delivered energy was as much as 25 per cent over fixed volume systems with fully-mixed tanks operating at conventional flow rates. The results were presented without inclusion of parasitic power requirements. If this is included, the relative improvement of the low flow rate systems is greater. It is conceivable that by making use of the mains pressure, a variable volume system could be constructed without a collector pump.

More work needs to be done in evaluating variable volume systems operating at low flow rates. In particular, it may be possible to identify collector flow control strategies that will provide greater improvements. The best strategy might inolve making control decisions based upon the current conditions and predictions of the future. As a separate topic, there is a need to determine whether the degree of stratification predicted by idealized models for fixed volume tanks operating at low collector flow rates is obtainable. The Hottel-Whillier model for a flat-plate collector should also be evaluated for accuracy at these low flow rates.

NOMENCLATURE

- A_c collector area
- b_0 incidence angle modifier constant, as defined by ASHRAE 93–77
- C_p constant-pressure specific heat of the collector working fluid
- C_v constant-volume specific heat of storage working fluid
- F' collector efficiency factor
- F_R collector heat removal efficiency factor
- $F_R(\tau\alpha)$ intercept of the collector efficiency versus $(T_i - T_a)/G_T$ curve corrected for non-normal solar incidence

- $F_R U_L$ negative of the slope of the collector efficiency versus $(T_i - T_a)/G_T$ curve
- FV-1N fixed volume system modeled with a fully-mixed (1 node) tank
- FV-3N fixed volume system modeled with a 3 node stratified tank
- FV-10N fixed volume system modeled with a 10 node stratified tank
- G_{TC} critical radiation level on the collector surface necessary for the collector pump to operate
- G_T instantaneous incident radiation on the collector surface per unit area
- $\bar{H}_T$ monthly-average daily incident radiation
- J constant of proportionality for flow control by radiation
- M mass of storage
- $\dot{m}_c$ instantaneous collector flow rate
- $\dot{m}_L$ instantaneous load flow rate
- M_L total monthly load flow
- $\dot{m}_r$ instantaneous flow rate recirculated from storage to the collectors
- N number of days in a month
- Q_μ instantaneous net useful energy collection
- t time
- T storage temperature
- T_a ambient temperature
- T_{env} environmental temperature
- T_i collector inlet temperature
- T_0 collector outlet temperature
- U_L overall loss coefficient of the collector
- $(UA)_t$ overall conductance for heat loss from tank
- VV–FF variable volume system with a fixed collector flow rate
- VV–FV variable volume system with variable collector flow rate controlled by radiation
- $\mathcal{F}$ fraction of the total energy delivered to the load plus auxiliary tank losses that is met by the solar system
- $\bar{\phi}$ fraction of the incident radiation that is above a specified fixed critical level
- $[\ ]_{test}$ refers to collector parameters at the test flow rate conditions
- $[\ ]_{use}$ refers to collector parameters at actual flow rate

REFERENCES

1. L. F. Jesch and A. Zekios, Adaptive control for a multiple tank, multiple temperature solar energy storage system. *Proc. ISES Silver Jubilee Congress*, Atlanta **1**, 852–856 (1979).
2. L. F. Jesch, T. W. Greeves and D. A. Haralambopoulos, Simulation of Control Strategies for Large Water Preheat Systems. *Proc. ISES Solar World Forum*, Brighton. **1**, 119–123 (1981).
3. L. F. Jesch, Solar energy storage in variable level tanks. *Proc. UKISES Midlands Branch Meeting*, pp. 99–104. M3, Birmingham (1982).
4. University of Wisconsin Solar Energy Laboratory, TRNSYS—A transient simulation program. *Engng Exp. Station Report* 38–11, Madison (1981).
5. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*. Wiley-Interscience, New York (1980).
6. C. W. J. van Koppen, J. P. Simon Thomas and W. Veltkamp, The actual benefits of thermal stratified storage in a small and a motion size solar system. *Proc. ISES Silver Jubilee Congress*, Atlanta. **1**, 576–580 (1979).
7. W. B. Veltkamp, Optimization of the mass flow in the best distribution circuit of a solar heating system with a stratified storage. *Proc. ISES Solar World Forum*, Brighton (1981).
8. W. F. Phillips and R. N. Dave, Effects of stratification on the performance of liquid-based solar heating systems. *Solar Energy* **29**, 111 (1982).
9. H. Tabor, A note on the thermosyphon solar hot water heater. *Bulletin C.O.M.P.L.E.S. No.* 17, 33 (1969).
10. R. L. Cole and F. O. Bellinger, *Natural Thermal Stratification in Tanks*, Argonne National Laboratory pp. 82–85, (1982).
11. A. H. Fanney and S. A. Klein, Performance of solar domestic hot water systems at the National Bureau of Standards—measurements and predictions. *ASME J. Solar Energy Engng* **105**, (1983).
12. S. A. Klein and J. C. Theilacker, An Algorithm for Calculating Monthly-Average Radiation of Inclined Surfaces. *ASME J. Solar Energy Engng* **103**, 29–33 (1981).
13. S. A. Klein, Calculation of flat-plate collector utilizability. *Solar Energy* **21**, 393 (1978).
14. M. Collaes-Pereira and A. Rabl, Simple procedure for predicting long-term average performance of nonconcentrating and concentrating solar collectors. *Solar Energy* **23**, 235 (1979).
15. R. G. Huget, *A Method for Estimating the Daily Utilizability of Flat-Plate Solar Collectors.* M.S. Thesis in Mechanical Engineering, University of Waterloo, Ontario (1981).
16. J. C. Theilacker and S. A. Klein, Improvements in the utilizability relationships. *Proc.* 1980 *Ann. Meet. AS/ISES*, Phoenix (1980).
17. D. L. Evans, T. T. Rule and B. D. Wood, A new look at long term collector performance and utilizability. *Solar Energy* **28**, 13 (1982).
18. D. R. Clark, S. A. Klein and W. A. Beckman, Algorithm for evaluating the hourly radiation utilizability function. *ASME J. Solar Energy Engng* **105**(3) (1983).