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THERMAL PERFORMANCE COMPARISONS FOR SOLAR HOT WATER SYSTEMS SUBJECTED TO VARIOUS COLLECTOR AND HEAT EXCHANGER FLOW RATES

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Abstract—The thermal performance of solar domestic hot water (SDHW) systems is influenced by the rate at which heat transfer fluids within the system are circulated. An experimental investigation has been conducted at the National Bureau of Standards to quantitatively evaluate the influence of flow rates, both for SDHW systems that circulate potable water directly through the solar collector array and for systems that employ an external heat exchanger to transfer heat from the solar collector array to the potable water. This article presents data from side-by-side experiments that shows improvements in overall SDHW system performance as a result of lowering the collector fluid flow rate for direct systems utilizing conventional return tubes. Although they are limited to one location, specific system configurations, and time periods, these experimental results support the general conclusions reached in earlier experimental and simulation studies regarding the advantage of reduced collector flow rate. Side-by-side experiments were also performed for SDHW systems in which the tanks were fitted with return tubes designed to reduce internal tank fluid mixing. The results of these experiments show only a small difference in overall performance for the systems operated at conventional and reduced collector flow rates. Side-by-side tests of an indirect SDHW system that employs an external heat exchanger did not show improved performance at reduced tankside flow rates. A simulation study of an indirect SDHW for a range of heat exchanger designs and collector and tankside capacitance rates concluded that an optimum collector-side capacitance rate does not exist and an optimum tank-side capacitance rate occurs only for heat exchangers with overall heat transfer coefficients much larger than that used in the experiments.

1. INTRODUCTION

This article describes the results of a combined experimental and simulation study of forced circulation solar domestic hot water systems (SDHW) that either circulate potable water through the solar collector array or employ an external heat exchanger to transfer heat from the solar collector array to the potable water. The study focuses on the effect collector array and tank-side heat exchanger flow rates have on the overall thermal performance of particular systems.

The most commonly employed control strategy for both of these systems has been the use of a differential temperature sensing controller to activate the circulator(s), which in turn circulate(s) the heat transfer fluid(s) at a fixed flow rate. Flow rates in SDHW systems have conventionally been selected to maximize the solar collector heat removal factor (and the heat exchanger energy transfer coefficient for indirect systems) while attempting to minimize parasitic power. The flow rates that result from this process are relatively high and result in average daily collector flow rates that are three or more times greater than the average daily load (i.e., hot water use).

The term "stratification," as used in this article, is defined as a measure of the difference between the maximum and minimum storage tank temperatures at a given time. Stratification can be increased by a reduction in collector flow rate, which permits a larger temperature increase in the collector fluid. Stratification may also be improved by measures designed to reduce mixing in the storage tank. In systems that do not employ a collector-tank heat exchanger, greater stratification results in a lower fluid temperature entering the solar collector and thus increased collector efficiency. Previous analytical and experimental investigations[1–15] have shown that the increase in collector efficiency resulting from increased tank stratification often outweighs the efficiency decrease resulting from a lower heat removal factor. The interaction between these two opposing factors results in an optimum flow rate of approximately 10 to 20% of that typically used in forced circulation direct systems. Veltkamp[5] and Wuestling et al.[9] conclude that for systems without a collector-tank heat exchanger, near-optimum performance is achieved when the monthly total water circulated through the collector array is approximately equal to the total monthly hot water requirement. However, the magnitude of the thermal performance improvement resulting from reduced collector flow rate in the Wuestling simulation study depends on tank model parameters that must be obtained experimentally. Side-by-side tests of SDHW systems operated at low and high collector flow rates were performed to determine whether the performance improvements cited by Wuestling and others were experimentally achievable over an extended period.

Earlier experiments have shown that the performance of direct SDHW systems operated at conventional collector flow rates can be improved through the use of collector fluid return tubes in the tank that reduces the momentum of the entering fluid and thereby reduces internal mixing and enhances stratification[10]. A series of experiments were conducted to determine whether operation of direct SDHW systems at low collector flow rates is still advantageous when stratification-enhancing return tubes are employed.

Solar hot water systems that employ a heat exchanger permit the use of a high collector array flow rate without directly promoting mixing within the storage tank. The flow rate through the tank side of the heat exchanger can be selected to promote stratification within the storage tank. However, reduced heat exchanger flow rates reduce the overall heat transfer coefficient of the heat exchanger. Side-by-side experiments and a simulation study were conducted to determine the advantage, if any, of reduced flow rates in indirect systems.

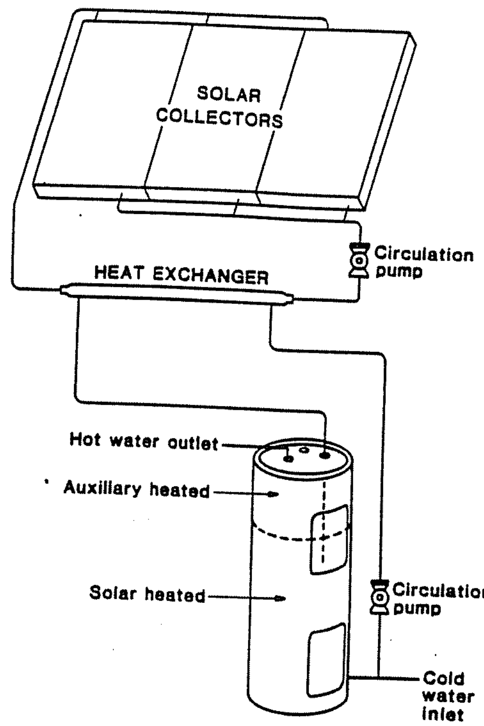

Fig. 2. Single-tank indirect solar hot water system.

2. EXPERIMENTAL APPARATUS

Two identical SDHW systems were fabricated at the National Bureau of Standards (NBS) Solar Hot Water Test Facility in Gaithersburg, MD. Each single-tank system may be operated with or without an external heat exchanger as shown in Figs. 1 and 2. A differential temperature controller actuates the circulator(s) when a temperature difference of 11.1°C exists between the absorber plate sensor and the storage tank sensor. When the temperature difference becomes less than 2.8°C, circulation ceases. In the direct mode, when the potable water is circulated through the collector array, a drain-down valve provides freeze protection if the absorber plate temperature is less than 3.3°C. The collector array of each system consists of three identical single-glazed flat-plate collectors connected in parallel, each having 1.4 m^2 of glazing area.

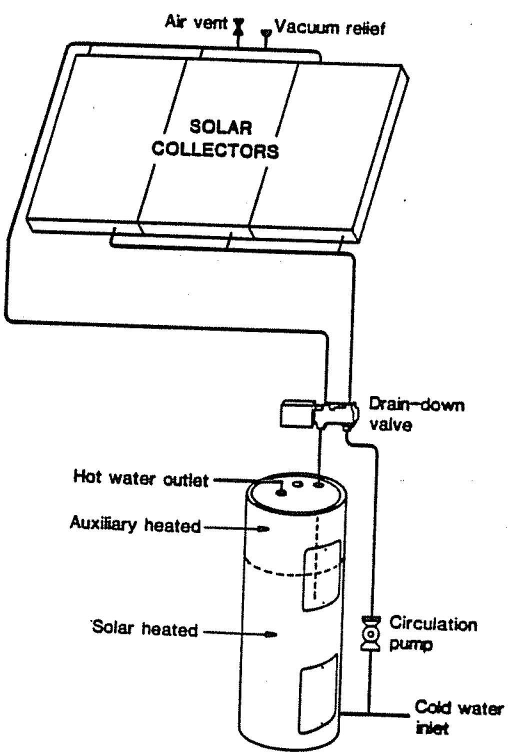

Fig. 1. Single-tank direct solar hot water system.

The storage tank for each system is a 0.303-m^3 conventional electric hot water tank with an experimentally measured overall energy loss coefficient of 2.8 W/° C and a height/diameter ratio of 2.5. The lower heating element is disconnected. The upper heating element, located 1.10 m above the bottom of the tank, is controlled by a thermostat that senses the storage tank temperature immediately above the element. The cold water supply temperature was maintained constant at 22.5°C. Although it is set at 60°C, the commercially available thermostats exhibit a considerable deadband. During normal operation, the thermostat typically energizes the heating element at approximately 54°C and disconnects the element at 60°C. Two different return tubes were used during this experimental investigation. One tube introduces the solar heated water into the storage tank as a single axial flow stream, Fig. 3a. The second return tube, Fig. 3b, redirects the downward axial flow into a number of radially directed flow streams. Commercially available, double-wall, shell-and-tube counterflow heat exchangers transfer heat from the collector fluid to the potable water when the solar systems are operated in the indirect mode. Dimensions of the all-copper heat exchanger are shown in Fig. 4.

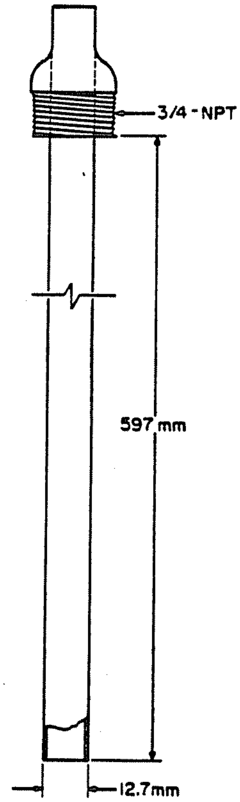

Fig. 3a. Standard return tube.

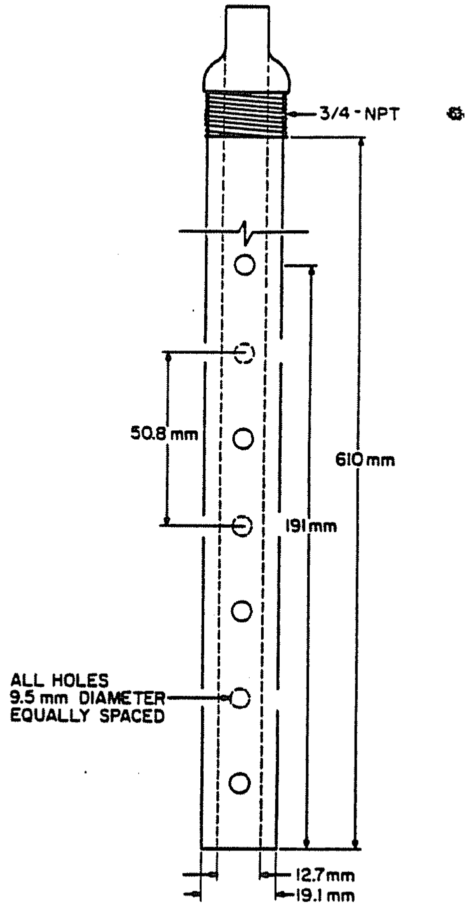

Fig. 3b. Stratification-enhancing return tube.

The solar hot water systems are extensively instrumented. Located within each storage tank are Type T copper-constantan thermocouples spaced in 152 mm increments along a vertical axis with the lowest thermocouple being 15 cm from the tank bottom. Six-junction thermopiles measure the temperature differential across the collector array, the shell and tube-side of the heat exchanger, and across the storage tank. The inlet and exit potable water temperatures are measured with thermocouples in conjunction with a three-junction thermopile. A digital watt-hour meter is used to measure the auxiliary energy consumed by the electric heating elements. A separate watt-hour meter measures the energy used by the circulator(s), controller, and drain-down valve for each system. The water consumption for each system is measured using a flow totalizer. Turbine flowmeters measure the rate at which the fluids circulate through the solar collector array and heat exchanger.

Recorded meteorological information includes horizontal surface radiation, tilted surface radiation, wind speed, wind direction, and ambient temperature. The output of all sensors is measured using a microcomputer-based data acquisition system that provides real time reduction of the experimental data.

3. EXPERIMENTAL RESULTS

3.1. *Solar collector array efficiency*

Experiments were conducted to determine the thermal efficiency of the entire solar collector array at various flow rates. All measurements were taken

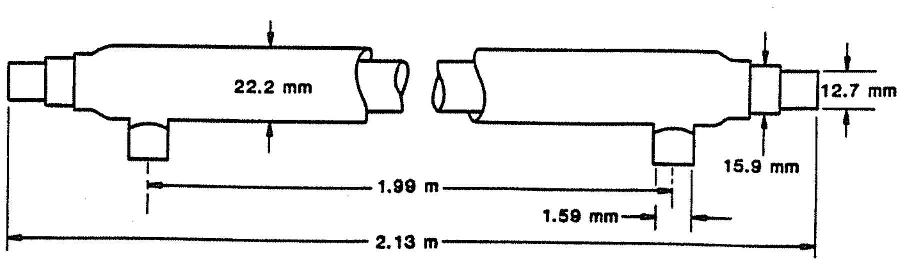

Fig. 4. Heat exchanger dimensions.

in accordance with ASHRAE Standard 93-77[16]. Figure 5 shows the efficiency curves for flow rates of 0.020 kg/s · m² and 0.0033 kg/s · m² using water as the heat transfer medium. At a flow rate of 0.020 kg/s · m², the slope and intercept of the test data result in collector parameters $F_R U_L = 5.0$ W/m²° C and $F_R(\tau\alpha)_\eta = 0.80$. The theory in Ref.[17] on the variation of F_R with collector flow rate indicates that $F_R U_L$ and $F_R(\tau\alpha)_\eta$ should be 4.3 W/m²° C and 0.69, respectively, at the 0.0033 kg/s · m² flow rate. The test values obtained from a least squares fit to the experimental data are $F_R U_L = 4.1$ W/m²° C and $F_R(\tau\alpha)_\eta = 0.68$.

Attempts made to determine the thermal performance of the collector array for flow rates less than 0.0033 kg/s · m² were unsuccessful because ASHRAE 93-77 specifies that tests shall only be performed when the solar irradiance incident on the aperture plane does not vary more than 32 W/m² for durations of two time constants, both prior to and during the period when data are taken. At a flow rate of 0.0033 kg/s · m², the collector array time constant was 16 min. Due to the long time constants associated with flow rates less than 0.0033 kg/s · m² and the use of a fixed test stand, it was impossible to meet this criteria under outdoor test conditions. This difficulty could be minimized by using an outdoor tracking collector test stand or by testing indoors using a solar simulator facility.

3.2. *Storage tank stratification*

During operation as a single-tank solar hot water system, internal storage tank temperature measurements were made at various collector array flow rates. Figure 6 shows the storage-tank temperature profile at a collector array flow rate of 0.02 kg/s · m² using the return tube shown in Fig. 3a. As noted in Ref. [2], the degree of stratification within the storage tank for this system is dependent on the operational status of the circulator. During the time interval when the pump is not energized, the tank is ordinarily stratified. During periods of solar energy collection, the circulation results in rapid mixing of the tank portion monitored by the lower seven thermocouples. The upper three thermocouples, located in the vicinity of the auxiliary heating element, show a rapid decay in temperature followed by a rapid increase in temperature during operation of the circulator. This rapid temperature decay is due to mixing between the solar heated portion of the tank and the upper auxiliary heated segment. As the temperature in the upper portion continues to decrease, the thermostat energizes the heating element resulting in a rapid temperature increase. The rate of temperature decay in the auxiliary heated section of the tank is significantly less during periods of no solar energy collection due to the lack of mixing within the storage tank. The storage tank temperature profile for a flow rate of 0.0033 kg/s · m² (taken at the same time as the data used to prepare Fig. 6) is shown in Fig. 7. Stratification exists at all times within the storage tank at this reduced flow rate. The upper three thermocouples show a

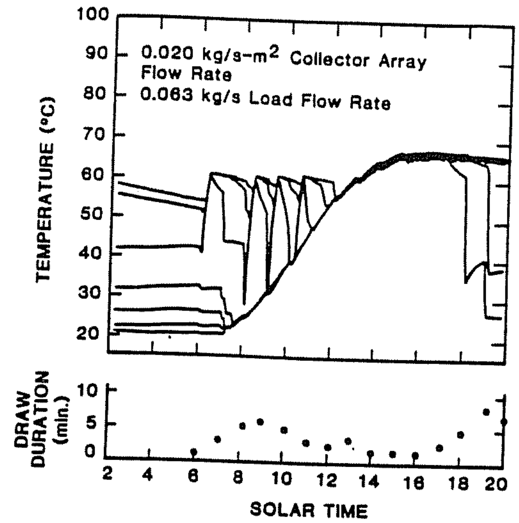

Fig. 6. Storage tank temperature profile at a collector flow rate of 0.02 kg/s · m².

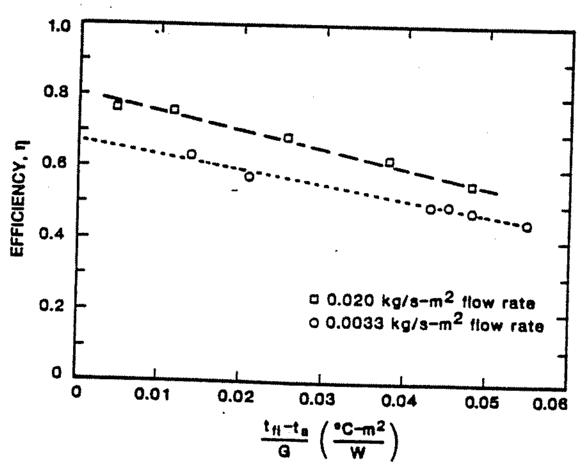

Fig. 5. Solar collector test results.

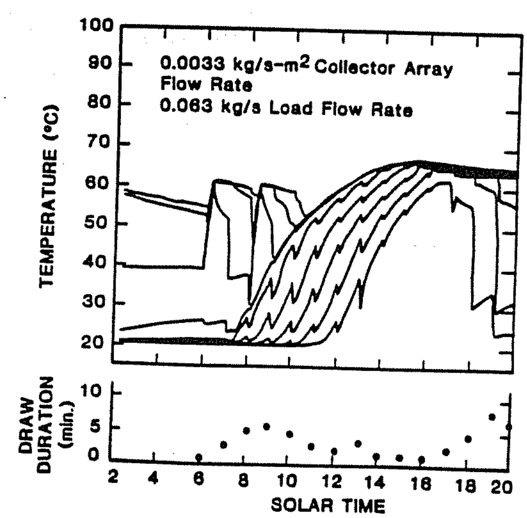

Fig. 7. Storage tank temperature profile at a collector flow rate of 0.0033 kg/s · m².

slower decay rate than Fig. 6, resulting in the thermostat energizing the auxiliary heating element only twice during the approximately 18-hour-long test period.

3.3. *Heat exchanger performance*

The overall heat-transfer area product, *UA*, was measured for three heat exchangers of identical construction subjected to various inlet temperature and flow rate conditions. During these tests, water was used in the shell side of the heat exchanger while a 50% (by weight) ethylene-glycol water mixture was circulated through the tube side. Figure 8 shows the measured heat-transfer area product as a function of the shell-side Reynolds number (defined in terms of the hydraulic diameter) for a constant tube-side Reynolds number of 11,000. Consultation with the manufacturer revealed that thermal performance differences of 15% or less were within the manufacturer's acceptable limits. Heat exchangers 1 and 3 were selected for additional characterization in an attempt to minimize differences in SDHW system performance. Additional tests were performed over a range of Reynolds numbers on both the tube and shell side of each of these two heat exchangers, as shown in Fig. 9.

3.4. *SDHW thermal performance comparisons*

In order to ensure that a thermal performance bias did not exist between the two side-by-side SDHW systems, short-term tests were conducted using identical flow rates. A thermal load was imposed on the SDHW systems during this and all subsequent comparisons by removing hot water, 265 l per day at a flow rate of 0.0632 kg/s, with a mains inlet temperature of 22.5° C in accordance with the RAND load schedule[18]. The resulting data revealed that when it was operated without heat exchangers, the solar energy delivered to the storage tank and electrical energy consumption were essentially equivalent for the two systems, well within the experimental measurement uncertainty. Data collected during tests in which the heat exchangers were installed, showed

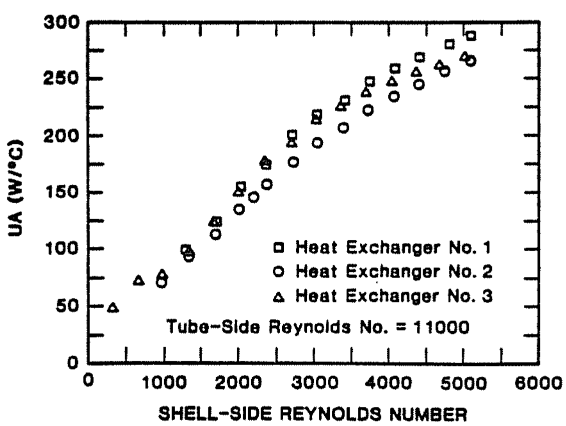

Fig. 8. Overall heat transfer coefficient area product for three heat exchangers as a function of shell-side Reynolds number.

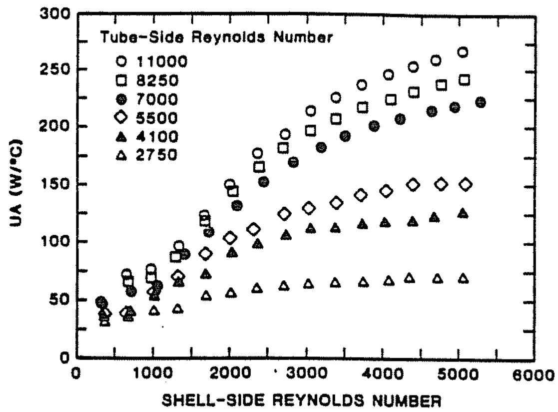

Fig. 9. Overall heat transfer coefficient area product as a function of shell- and tube-side Reynolds numbers.

that under equivalent flow rate conditions, the solar energy delivered and auxiliary energy consumption were again within measurement uncertainty of being equivalent. Upon conclusion of the initial comparisons, experiments were conducted to document the influence of collector array and heat exchanger flow rates on the overall performance of SDHW systems. The results are presehted in the following discussion.

The first experiment consisted of operating both SDHW systems in the single-tank direct mode. During a seven day test interval, May 4 to 10, System A utilized a collector array flow rate of 0.020 kg/s · m^2 in accordance with the collector manufacturer's recommendations. The array flow rate selected for System B, 0.0033 kg/s · m^2, was based on observations of storage tank stratification and the desire to use a flow rate in the vicinity of that identified as the optimum by Velkamp[5] and Wuestling et al.[9]. The lower array flow rate utilized in System B resulted in a 8% increase (±2%) in solar energy delivered to the storage tank and a 10% decrease (±0.5%) in auxiliary energy consumption. The lower array flow rate in System B permitted the use of a slower circulator speed resulting in a reduction of parasitic energy for system B even though the elapsed operational time was significantly greater, 38.6 versus 25.1 hours. The average daily circulation times for this period are relatively low due to poor solar conditions and translate into collector to load flow ratios of 4.1 for System A and 1.0 for System B.

During the second experiment, May 22 to 30, the collector array flow rates were reduced to 0.0033 kg/s · m^2 and 0.0025 kg/s · m^2, respectively, for Systems A and B. An 8.7% (±2%) reduction in auxiliary use and a 32% (±0.5%) reduction in parasitic energy were observed (accompanied by an increase in solar energy delivered) for the system with the lower flow rate. The collector to load flow ratios for this 9-day period were 1.27 and 1.1, respectively, for System A and B. Additional reductions in the collector array flow rate resulted in flow imbalances among the collectors and subsequent poor system performance. The imbalanced flow condition was detected by monitoring thermocouples attached to the absorber plates.

Based on the experimental results just discussed, a reduced collector array flow rate for System B of 0.0025 $kg/s \cdot m^2$ was selected for long-term comparisons. The results for a 24-day comparison, June 7 to 30, are given in Table 1. The solar energy delivered to the storage tank was approximately 17% greater (±2%) for the system with the lower collector array flow rate. The auxiliary energy consumption was reduced by 37% (±.5%) and a 17% (±.5%) reduction in parasitic energy was observed. The ratio of the collector flow to load flow for the 24-day period was 7.5 for System A as opposed to 1.3 for System B.

The uncertainty associated with each experimental variable in Tables 1 to 5, computed using the method of Kline and McClintock[19], are presented in Table 6. Note that the use of the performance indices, e and e_{PAR}, in Tables 1 through 5 permit the computation of overall system performance without utilizing measurements that have a high degree of uncertainty. For example the fractional energy savings, e, defined as

$$e = 1 - \frac{Q_{aux}}{Q_{conv}}$$

required that only the auxiliary energy and thermal load be measured. The uncertainty associated with these quantities is relatively low, and thus the uncertainty in the fractional energy savings, e is within ±1.5%.

A previous NBS investigation[10] revealed that the performance of direct SDHW systems could be improved through the use of return tubes that enhance storage tank stratification. A series of side-by-side experiments were conducted during which the return tubes depicted in Fig. 3b were installed in both systems. The results presented in Table 2 show only small improvements in overall system performance with the reduced collector flow rate. The largest improvement was observed during the January 17-to-21 test period during which the solar energy collected was approximately 6% greater for the system using the reduced flow rate resulting in a four percentage point increase in the fractional energy savings. The February 6 to 20 period showed essentially no performance improvement. However, the collector-to-load ratios for this period were very low due to poor solar conditions and the 0.3 value for the low flow system is significantly below the optimum value of (approximately) 1.

An additional side-by-side comparison was conducted in which the stratification enhancing return tube (Fig. 3b) was removed from System B and replaced with the standard return tube (Fig. 3a). The stratification enhancing return tube remained in System A. The array flow rate in System A was set at 0.0200 $kg/s \cdot m^2$ as compared to the 0.0033 $kg/s \cdot m^2$ flow rate utilized in System B. This 10-day side-by-side comparison, Table 3, permitted a direct comparison between a SDHW System equipped with the stratification enhancing return tube and operated at normal flow rate conditions, with an SDHW system operated at low flow rate conditions equipped with a standard return tube. Table 3 shows that the solar energy delivered to the storage tank for System B was only slightly greater than for System A. The results appear to be in agreement with the results of Karaki et al.[15], who concluded that when effective stratification devices are used within storage tanks, little difference in daily energy collected is observed for identical systems utilizing high and low flow rates.

The freeze protection valves were removed from each system and the counterflow heat exchangers were installed for the next series of tests. The 50% by weight ethylene-glycol mixture was circulated through the collector array of both systems at a rate of 0.0151 $kg/s \cdot m^2$. The flow rate through the tank side of the heat exchanger was set to 0.083 kg/s (0.020 $kg/s \cdot m^2$) for System A whereas the corresponding flow rate for System B was maintained at 0.0104 kg/s (0.0025 $kg/s \cdot m^2$). During the 16-day test period (see Table 4), the auxiliary energy consumed by the system with the lower rate of circulation through the tank side of the heat exchanger was 6.6% greater in comparison to that consumed by the system with the higher tank-side flow rate. The advantages of enhanced stratification within the storage tank did not offset the thermal penalty imposed by the heat exchanger in this system. The use of a slower circulator speed did result in lower parasitic energy consumption for System B. This reduction, however, was not sufficient to offset increased auxiliary energy consumption. Additional results, not presented here, showed that further lowering the flow rate on the tank side of the heat exchanger reference did not result in improved SDHW system performance.

For the next series of tests, the hot water systems were converted from single-to double-tank SDHW systems by disconnecting the upper heating element in the 0.303 m^3 tanks and adding downstream 0.151

Table 1. Thermal performance comparisons for single-tank direct SDHW systems with standard return tubes

Comparison period system	June 7–30, 1985 A	B
Collector flow rate [$kg/s \cdot m^2$]	0.0200	0.0025
Q_{solar} [MJ]	826.5	967.1
Q_{loss} [MJ]	149.0	149.5
Q_{load} [MJ]	927.6	946.3
Q_{aux} [MJ]	216.0	135.1
Q_{stored} [MJ]	−0.3	−0.5
Q_{conv} [MJ]	1195.4	1213.1
e	0.82	0.89
Circulated elapsed time [h]	159.5	223.2
P_{WC} [W]	96	57
Q_{par} [MJ]	55.1	45.8
e_{PAR}	0.77	0.85
Collector/load flow ratio	7.6	1.3

Table 2. Thermal performance comparisons for single-tank direct SDHW systems with stratification enhancing return tubes

	Jan. 17–21, 1986		Feb. 6–20, 1986		Mar. 15–20, 1986	
Comparison period system	A	B	A	B	A	B
Collector flow rate [kg/s · m²]	0.020	0.0043	0.020	0.0025	0.020	0.0033
Q_{solar} [MJ]	76.6	81.3	117.5	112.6	149.2	155.2
Q_{loss} [M]	20.1	19.7	57.0	54.5	30.0	28.8
Q_{load} [MJ]	202.1	202.1	590.3	591.1	232.9	234.5
Q_{aux} [MJ]	143.1	134.1	530.7	525.4	105.2	98.4
Q_{stored} [MJ]	2.5	−0.8	2.3	1.8	−1.4	−0.5
Q_{conv} [MJ]	257.9	257.9	757.7	758.5	299.9	301.5
e	0.45	0.48	0.30	0.31	0.65	0.67
Circulator elapsed time [h]	13.4	15.6	19.5	28.8	26.6	39.9
P_{WC} [W]	96	57	96	57	96	57
Q_{par} [MJ]	4.6	3.2	6.8	5.9	9.2	8.2
e_{PAR}	0.43	0.47	0.29	0.30	0.62	0.65
Collector/load flow ratio	3.06	0.77	1.48	0.27	5.06	1.25

m³ hot water tanks with an experimentally measured energy loss coefficient of 1.95 W/°C, Fig. 10. Standard return tubes were used in both 0.303 m³ tanks. Side-by-side comparisons were conducted from May 16 through May 26. The collector flow rate for System A was maintained at 0.020 kg/s · m² while a reduced collector flow rate of 0.0033 kg/s · m² was utilized in System B. During this 11-day test period, the auxiliary energy consumption was approximately 9% less (±0.5%) for the system utilizing the reduced flow (see Table 5).

4. SIMULATION RESULTS

Wuestling et al.[9] report simulated performance improvements between 11 and 15% as a result of using optimal collector flow rates that were found to occur at a collector to load flow ratio of about 1.0. However, this conclusion was based on the assumption that the storage tank is fully mixed at high collector flow rates. Furthermore, the storage tank model used in the study was not verified experimentally. Simulations of the systems investigated experimentally were conducted in an attempt to validate the model and thus the general conclusions of the Wuestling study.

The simulation models were constructed with the standard collector, water storage tank, controller, and auxiliary heater component models from the TRNSYS[20] library. Parameter values were chosen based on the physical description of the systems. Piping losses were judged to be small and were neglected in the simulations. The collector parameters, $F_R(\tau\alpha)_n$ and F_RU_L, for systems operated at a collector flow rate of 0.020 kg/s · m² were taken from Fig. 5. However, measured values of the collector parameters were not available at a flow rate of 0.0025 kg/s · m². In this case, the experimental values for a flow

Table 3. Thermal performances comparisons of single-tank SDHW system performance with standard and stratification enhancing return tubes

	March 31–April 9, 1986	
Comparison period system	A	B
Return tube configuration	Stratification enhancing	Standard
Collector flow rate [kg/s · m²]	0.0200	0.0033
Q_{solar} [MJ]	336.1	342.6
Q_{loss} [MJ]	63.6	58.9
Q_{load} [MJ]	434.7	435.0
Q_{aux} [MJ]	142.9	135.8
Q_{stored} [MJ]	−8.0	2.5
Q_{conv} [MJ]	546.3	546.6
e	0.74	0.75
Circulator elapsed time [h]	51.4	66.6
P_{WC} [W]	96	57
Q_{par} [MJ]	17.8	13.7
e_{PAR}	0.71	0.73
Collector/load flow ratio	5.86	1.25

Table 4. Thermal performance comparisons for single-tank indirect SDHW systems

	October 12–27, 1985	
Comparison period system	A	B
Collector-side flow rate [kg/s · m²]	0.0151	0.0151
Tank-side flow rate [kg/s · m²]	0.020	0.0025
Q_{solar} [MJ]	364.0	354.6
Q_{loss} [MJ]	79.8	68.7
Q_{load} [MJ]	659.7	666.9
Q_{aux} [MJ]	355.8	379.2
Q_{stored} [MJ]	0.58	0.76
Q_{conv} [MJ]	838.3	845.5
e	0.58	0.55
Circulator elapsed time [h]	82.3	110.0
P_{WC} [W]	96	57
P_{EWC} [W]	185	185
Q_{par} [MJ]	83.3	95.8
e_{PAR}	0.48	0.44
Tank-side/load flow ratio	5.9	0.98

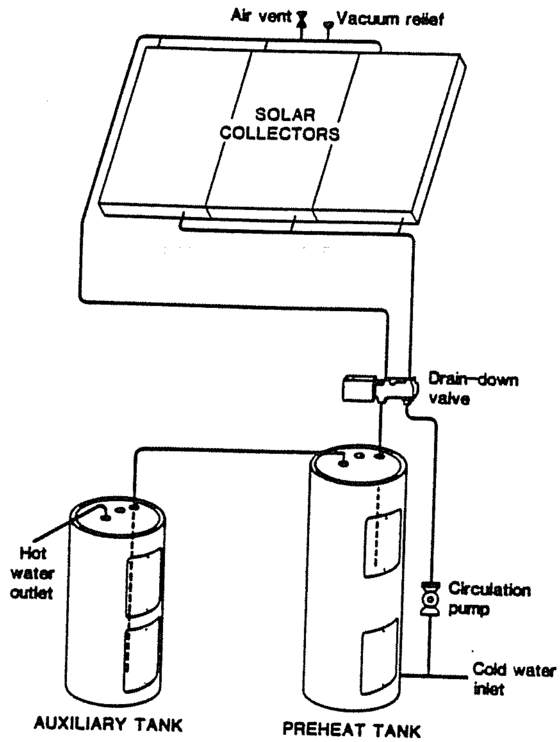

Fig. 10. Double-tank direct solar hot water system.

rate of 0.0033 $kg/s \cdot m^2$ given in Fig. 5 were extrapolated using the method described in Duffie and Beckman[17] to a flow rate of 0.0025 $kg/s \cdot m^2$. The simulations used measured hourly solar radiation and ambient temperature data for the same periods as the experiments.

Both multinode and plug-flow models are available in the TRNSYS library. The multinode model simulates thermal stratification by dividing the tank into a user-specified number of constant volume segments. Energy balances on the segments result in differential equations that yield the average temperature of the water within each segment. The degree of thermal stratification is controlled by the number of tank segments. A one-segment model simulates a fully mixed tank. As the number of tank segments is increased, internal mixing is decreased and a higher degree of thermal stratification is achieved. At low collector flow rates, it may be necessary to have 50 or more segments to adequately represent the limiting case of no internal mixing[5], although TRNSYS currently allows only 15 segments in the multinode model.

The plug-flow tank model used by Wuestling et al. simulates the behavior of a temperature stratified storage tank using a variable number of variable fluid size segments. As with the multinode model, a larger number of (smaller) tank segments results in less internal mixing and improved stratification. Thermal conduction is not accounted for in the plug-flow model; however, previous investigations have shown that the effects of thermal conduction are negligible for the tank geometries considered here, even for the low collector flow rate with highly stratified conditions in the tank[21]. The maximum number of tank segments in current plug-flow model is 50, but the number of tank segments actually employed and their volumes vary depending primarily on the tank volume, the net (collector plus load) flow and the simulation time step. Entering fluid is assigned a tank segment volume equal to the net flow of water through the tank during the simulation time step. The net flow of water (and thus the average volume of the tank segments) increases with increasing flow rates and with larger time steps. Thus, the accuracy of the plug-flow model in describing perfect thermal stratification is controlled both by the collector and load flow rates and by the user-selected simulation time step. The effect of time step on the fractional energy savings for the one and two-tank direct systems is shown in Fig. 11 for the conditions represented in Table 1.

The TRNSYS tank models provide two options (fixed inlet and variable inlet) for simulating the flow of water into the tank. The fixed inlet option forces the inlet water to enter the tank section in which the inlet is physically located, regardless of the temperature of the water in the tank at this position. This option introduces some mixing at the inlets. Tem-

Table 5. Thermal performance comparisons for double-tank direct SDHW systems with standard return tubes

	May 11–26, 1986	
Comparison period system	A	B
Collector flow rate [$kg/s \cdot m^2$]	0.020	0.0033
Q_{solar} [MJ]	574.3	588.1
Q_{loss} [MJ]	173.5	166.8
Q_{load} [MJ]	681.1	675.1
Q_{aux} [MJ]	293.8	266.9
Q_{stored} [MJ]	6.0	10.5
Q_{conv} [MJ]	803.9	797.9
e	0.64	0.67
Circulator elapsed time [h]	99.9	138.3
P_{WC} [W]	96	57
Q_{par} [MJ]	34.5	28.4
e_{PAR}	0.59	0.63
Collector/load flow ratio	7.1	1.6

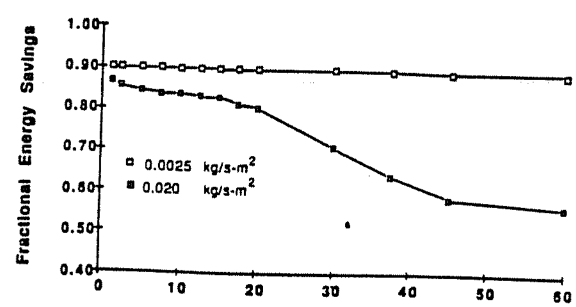

Fig. 11. Effect of time step on simulation results using the plug-flow model for the conditions of Table 1.

Table 6. Uncertainty associated with measured quantities presented in Tables 1–6

Variable	Uncertainty (%)
Collector flow rate	±1.0
Q_{solar}	±2.2
Q_{loss}	±5.0
Q_{load}	±1.5
Q_{aux}	±0.5
Q_{stored}	±100.0
Q_{conv}	±1.5
e	±1.5
Circulator elapsed time	±0.01
P_{WC}	±1.0
Q_{par}	±0.5
e_{PAR}	±1.5

perature inversions within the tank are eliminated by mixing segments above and below the inlets, as necessary. With the variable inlet option, inlet water is directed to the level to which it is closest in temperature which results in less internal mixing (more stratification) than the fixed inlet option. Wuestling et al.[9] used the variable inlet option in their study and this option was employed in the results used to generate Fig. 11.

Either storage tank model can be applied to determine limits on system performance. A tank that has no stratification is simulated by the multinode model with one tank segment. Maximum stratification is simulated by either the multinode model with many segments or by the plug-flow model with short time steps with the variable inlet option. The performance of an actual tank should lie within these limits.

Figure 11 shows that the difference in the fractional energy savings between low and high collector flow rate operation of the direct systems depends on the chosen time step for the plug-flow model. When maximum stratification is simulated using small time steps, the results show small differences in system performance at low and high collector flow rates. This observation is in agreement with the experimental data (Table 2) for which the two side-by-side systems were equipped with return tubes that promote stratification. At low collector flow rates, the simulation results obtained for maximum stratification agree well with the experimental results. However, the assumption of maximum stratification overestimates the performance at high collector flow rates. The model does not account for internal mixing within the tank that apparently occurs to some extent at the high flow rates. On the other hand, the fully mixed preheat tank (or preheat tank section in the case of the one-tank systems) consistently underpredicts the experimental performance in all cases, which indicates that some amount of thermal stratification occurs, even in the high flow rate systems.

Figure 11 demonstrates that the time step has no significant effect on the calculated results at the low collector flow rate. At a flow rate of 0.020 kg/s · m^2, however, the calculated performance decreases markedly as the time step increases. The decrease in performance is due to mathematical dispersion or mixing, a result of inaccurate numerical solution of the governing equations. Wuestling et al. used a 30-min time step to produce most of the results in their study. However, the maximum collector flow rate investigated in the Wuestling et al. study was 0.0139 kg/s · m^2 for which an increasing time step has less of an effect than observed for the 0.020 kg/s · m^2 flow rate in Fig. 11. It is apparent from Fig. 11 that the performance advantage of low collector flow cannot be determined using the existing models without some experimental data.

Table 7 compares simulation results obtained using the plug-flow model with 15 minute time steps with experimental data for the one-tank direct system. The simulated thermal performance is in good agreement with the experimental data. Apparently, the 15-minute time step introduces an amount of numerically caused dispersion, dependent on the collector flow rate, which is representative of the tank design and conditions actually occurring in these experiments.

Because pipe losses and thermal capacitance effects were not considered in the simulation, the simulated performance should be somewhat better than

Table 7. Comparison of experimental and simulation results for single-tank direct SDHW systems using plug-flow TRNSYS model with 15 min time steps, June 7–30, 1985

	System A		System B	
	Experiment	Simulation	Experiment	Simulation
Flow rate [kg/s · m^2]	0.020	0.020	0.0025	0.0025
Q_{solar} [MJ]	826.5	842.4	967.1	1041.0
Q_{loss} [MJ]	149.0	135.2	149.5	132.0
Q_{load} [MJ]	927.6	924.5	945.3	105.7
Q_{aux} [MJ]	216.0	207.5	135.1	135.7
Q_{stored} [MJ]	−0.30	−10.1	−0.50	−11.9
Q_{conv} [MJ]	1195.4	1192.3	1213.1	1324.8
e	0.82	0.826	0.89	0.897
Circulator elapsed time [h]	159.5	172.5	223.2	254.8
Collector/load flow ratio	7.6	7.3	1.5	1.7

experimentally measured. However, a direct comparison is confounded by the fact that the loads on the experimental and simulated systems are not identical. Both the experimental and the simulation results show the load to increase as the collector flow rate is reduced although the volume draws are the same in all cases. The increase occurs because the low flow rate systems provide water above the set temperature more often than the high flow rate systems in a one-tank configuration. This effect occurs to a larger extent in the simulations, due to lack of consideration of piping effects. A noticeable difference between the experimental and simulation results appears in the collector circulator elapsed times. The primary cause for this discrepancy is the lack of consideration of thermal capacitance effects and transport times.

Simulations of the indirect systems were also run. A TRNSYS component was developed to calculate the heat exchanger overall heat transfer coefficient using the data in Fig. 9 and simulations were run to investigate other collector and tankside flow rate combinations and heat exchanger designs[21]. The simulations showed that, for the conditions represented in Table 4, better performance is obtained with the higher tank-side flow rates, as was seen in the experimental results. For the heat exchanger used in the experiments, optimum flow rates were found not to exist; that is, the thermal performance continuously improved with increasing collector and tank-side flow rates. However, an optimum tankside flow rate occurred for heat exchangers with large overall heat transfer coefficients and this optimum flow rate decreased as the overall heat transfer coefficient of the heat exchanger increased. To take advantage of enhanced stratification at low tankside flow rates, the heat exchanger heat transfer coefficient would have to be more than five times larger than that used in the experiments.

5. DISCUSSION AND CONCLUSIONS

Experiments conducted at the National Bureau of Standards Solar Hot Water Test Facility revealed that the performance of a typical single-tank direct SDHW system can be substantially improved by utilizing a reduced flow rate in a storage tank with a standard return tube. The improved thermal performance is attributed to better stratification within the solar storage tank and a significant reduction in mixing, which occurs between the solar and auxiliary heated portions in a single-tank system. The experimental results support the results of Wuestling et al. concerning the existence of an optimum flow rate, but the magnitude of the performance improvement resulting from reduced collector flow was not as large as the simulation study indicated. The direct systems that employed stratification enhancing return tubes were found to benefit only slightly through the use of reduced flow rates.

It appears that manufacturers striving to improve system performance may take either of two approaches. The first approach would be to simply reduce the flow rate. This approach provides system designers the opportunity to improve system performance while concurrently reducing equipment costs through the use of smaller diameter tubing connecting the collector array to the storage tank, the use of smaller circulation pumps, and the use of smaller riser tubes within the solar collectors. However, the use of greatly reduced flow rates should be approached with caution because flow imbalances in the solar collector array can occur. The second approach would be continue to operate at typically used flow rates and provide a means of enhancing stratification within the storage tank. This approach requires additional capital investment but avoids the potential of flow imbalances within the solar collector array.

Improved thermal performance for the indirect SDHW system that employs a heat exchanger to transfer energy from the solar collector to the potable water, was not observed by reducing the flow rate through the storage tank side of the heat exchanger. This result can be explained by the significant decrease in heat exchanger energy transfer coefficient resulting from the lower flow rate. The heat exchanger penalty more than offset the improved stratification within the storage tank and simulations showed that this would always be the case unless the overall heat transfer coefficient of the heat exchange were much larger.

The use of reduced flow rates in SDHW systems should be approached cautiously. The optimum flow rate depends on numerous factors including array size, storage tank capacity, and the load imposed on the system. Flow imbalances may occur if the collector array flow rate is reduced below a certain level. Manufacturers will need to conduct outdoor side-by-side testing or controlled indoor testing to determine the optimum flow rate.

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NOMENCLATURE

- e fractional energy savings excluding parasitic energy consumption, (defined as $1 - Q_{aux}/Q_{conv}$), [dimensionless]
- e_{PAR} fractional energy savings including parasitic energy consumption, [dimensionless]
- F_R collector heat removal factor, [dimensionless]
- G total global irradiance incident upon the aperture plane of the collector, [W/m^2]
- K incident angle modifier, [dimensionless]
- P_{WC} electrical power input to three-speed water circulator, [W]

P_{EWC} electrical power input to pump used to circulate ethylene glycol water mixture, [W]

Q_{aux} energy consumed by storage tank heating element(s), [MJ]

Q_{conv} energy required by a conventional electric water heater to meet the thermal load imposed on the solar hot water heater (thermal losses from the conventional heater are assumed to be 11.2 MJ per day), [MJ]

Q_{load} energy extracted from solar hot water system including the auxiliary contribution, [MJ]

Q_{loss} thermal losses from storage tank(s), [MJ]

Q_{stored} increase in storage tank internal energy during test period, [MJ]

Q_{tank} solar energy delivered to storage tank, [MJ]

Q_{par} electrical energy consumed by circulator(s) and controller, [MJ]

t_a ambient temperature, [°C]

t_{fi} fluid temperature entering the collector array, [°C]

UA overall heat transfer coefficient-area product, [W/°C]

θ angle of incidence between the direct solar beam and the normal to the collector aperture, [deg]

η collector efficiency based on the net area, [dimensionless]

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